3.0 SOUTHWEST MONSOON REGIME (JUN-SEP)

3.1 General Description

The Southwest (summer) Monsoon in our area of interest is characterized by strong surface heat troughs over the surrounding land areas -- particularly over India, Pakistan, Iran and Saudi Arabia.

From the standpoint of surface wind direction over the Arabian Sea, the Southwest Monsoon is typically well established by June; however, the rainy season along the west coast of India does not normally commence until somewhat later (as early as June 1 in southernmost India but as late as July 2 in Karachi). Surface winds reach a maximum in July with the highest speeds (up to 50-60 kt) reported northeast of Socotra Island where winds greater than 33 kt occur more than 30 % of the time.[1] As a result of these consistently strong winds, sea heights of 8 ft or higher persist over more than half of the Arabian Sea during this season.[2]

Upper level winds (above 400 mb) over our area of interest are easterly during the Southwest Monsoon. The Himalayan mountains help to produce and anchor an intense upper anticyclone near 30°N and 85°E (Sadler, 1975). Between this anticyclone and the subtropical ridge of the Southern Hemisphere exist the most extensive and strongest upper tropospheric easterlies within the tropics.

Figure 3-1 is a mosaic of satellite visual images showing a broad area enclosing the Indian Ocean during the Southwest Monsoon regime. Cloud patterns clearly show the directions of the low-level and high-level wind flow in the Arabian Sea, the heavy convective activity over India and a procession of cold surges in the Southern Hemisphere.

There is considerable variability in the time of onset of the Southwest Monsoon, in its intensity once established and in the time at which it ends. At either end of this season, the southwest winds are not persistent; they occur in periods separated by variable or even northeasterly winds. Fluctuations in surface wind intensity during the heart of this monsoon regime are <u>not</u> correlated with the central pressure of the surface heat troughs over land but rather, with the distribution of the pressure gradient over the Arabian Sea. Details concerning the onset of the Southwest Monsoon and breaks within this monsoon regime are presented in Sections 3.2.3 and 3.2.5 respectively.

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1. Naval Weather Service Detachment, Asheville, 1974.
2. Ibid.

Figure 3-1. This mosaic is representative of a moderately active Southwest Monsoon situation. The west coast of India and the Central Arabian Sea are cloudy while generally cloud-free conditions prevail over the Red Sea, Gulf of Aden, Persian Gulf, Gulf of Oman, and the Arabian Peninsula. In the typical Southwest Monsoon flow, cloud amounts and the vertical extent of clouds increase from west to east across the Arabian Sea, and the low-level cloud lines parallel the near-surface wind flow. In this example, a thick dust cloud covers the northwestern part of the Persian Gulf and a thin dust veil extends southeastward almost to the Strait of Hormuz (the narrow passage between the Persian Gulf and the Gulf of Oman). Cirrus streamers clearly indicate the direction of the upper-level easterlies. Outside of our particular area of interest, there is a monsoon depression over the western Bay of Bengal and a series of cold-frontal bands forming a procession of cold surges in the Southern Hemisphere. (The northeastern Arabian Sea is shown in greater detail in Figure 3-6, which was recorded on the same date.)

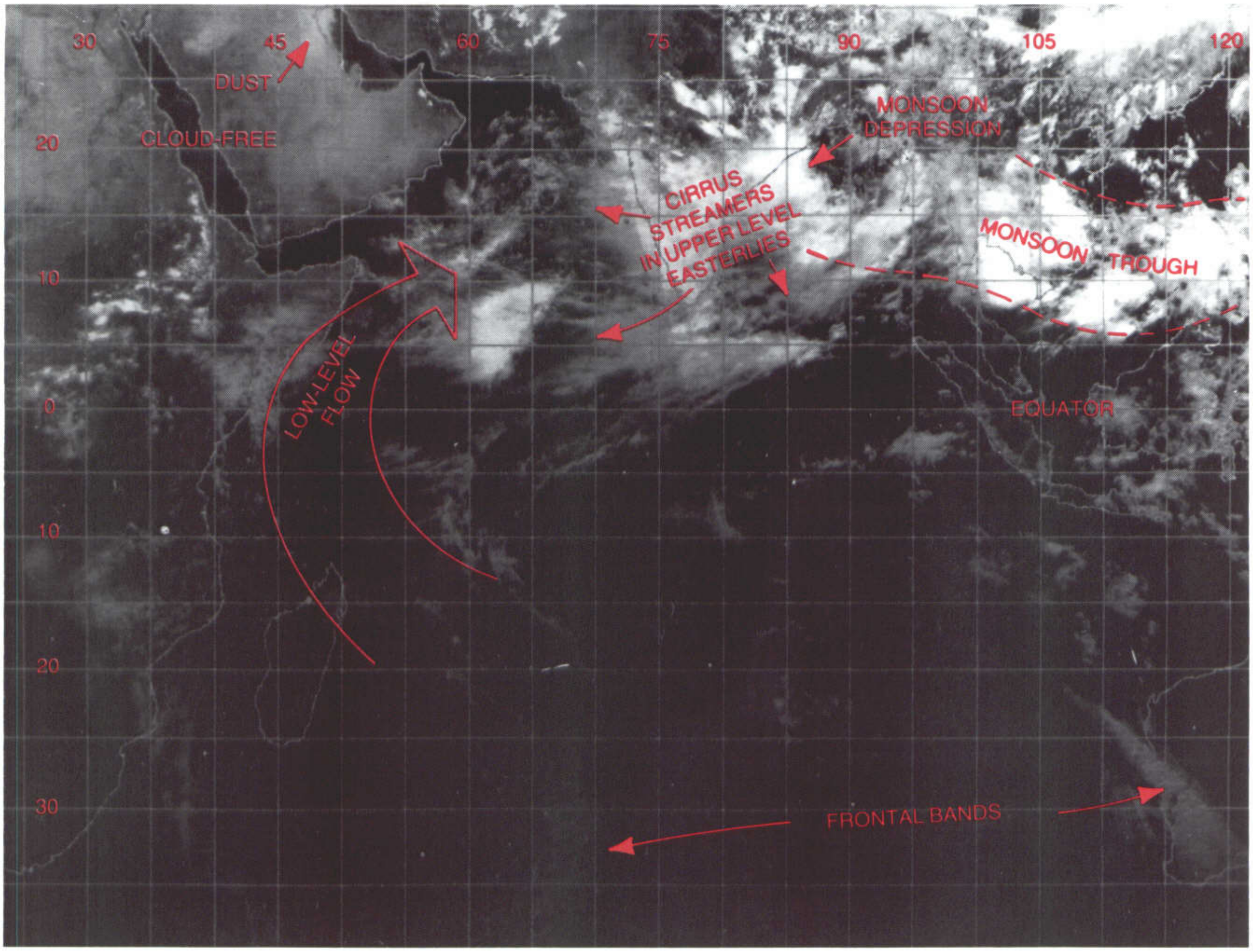


Figure 3-1. NOAA visual mosaic image produced from data recorded on June 23, 1979.

3.2 Large-Scale Circulation Features

The Asian-African monsoon climate results from the unique geography of the Eastern Hemisphere. The nearly continuous east-west mountain range barrier (see Figure 2-3) greatly inhibits normal low tropospheric air flow and meridional heat exchange. In summer, the resultant heat surplus creates intense surface heat lows over land capped by an intense high pressure ridge along the southern edge of the barrier.

3.2.1 Climatology

Naval Oceanography Command climatological publications (see Appendix A) contain monthly or seasonal data for several operationally significant parameters. It is not the purpose of this Handbook to duplicate existing publications; however, for ready reference and to illustrate the discussion which follows, Figures 3-2a through e provide pertinent climatological data which are representative of the Southwest Monsoon regime. The data from which the figures are derived were not uniformly distributed over the region. In particular, Figure 3-2c, d and e are biased by observations from coastal and island stations; therefore, detail and reliability are reduced over the open ocean. In spite of these limitations, the following climatological charts provide a summary of pertinent parameters and a baseline for the application of the material in this Handbook to daily forecasting problems.

3.2.2 Heat Low and Monsoon Trough

Terms applied to weather phenomena, particularly in tropical regions, tend to defy standardization. In this Handbook, the following definitions apply:

a. Heat Low (or Thermal Low): "An area of low atmospheric pressure due to high temperatures caused by intensive heating at the earth's surface. Thermal lows are common to the continental subtropics in summer; they remain stationary over the area that produces them; their cyclonic circulation is generally weak and diffuse; they are non-frontal." (Huschke, 1959)

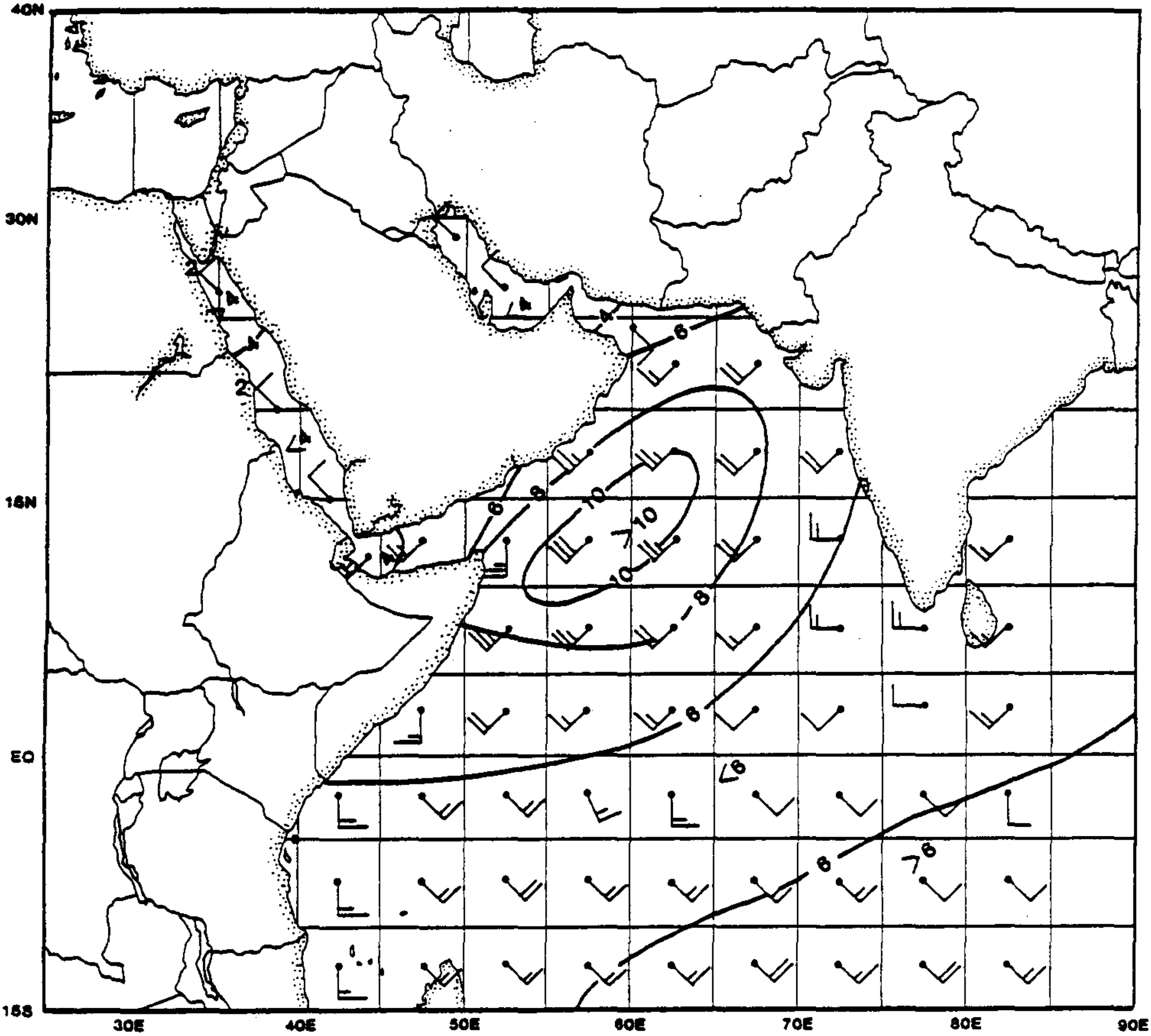


Figure 3-2a. Mean July surface winds (wind barbs) and seasonal mean significant wave heights in feet (contours) (adapted from Naval Weather Service Detachment, Asheville, 1974). The winds represent the average over a 5° rectangle of latitude and longitude. Wind barbs representing the restricted waters of the Red Sea, Persian Gulf and the Gulfs of Aden and Oman are plotted over the water area that they represent. The height contours underspecify wave conditions for mid-June to mid-August for two reasons: (1) the months June through September are averaged, and (2) the data upon which the means are based considered only the higher of the wave and swell components reported.

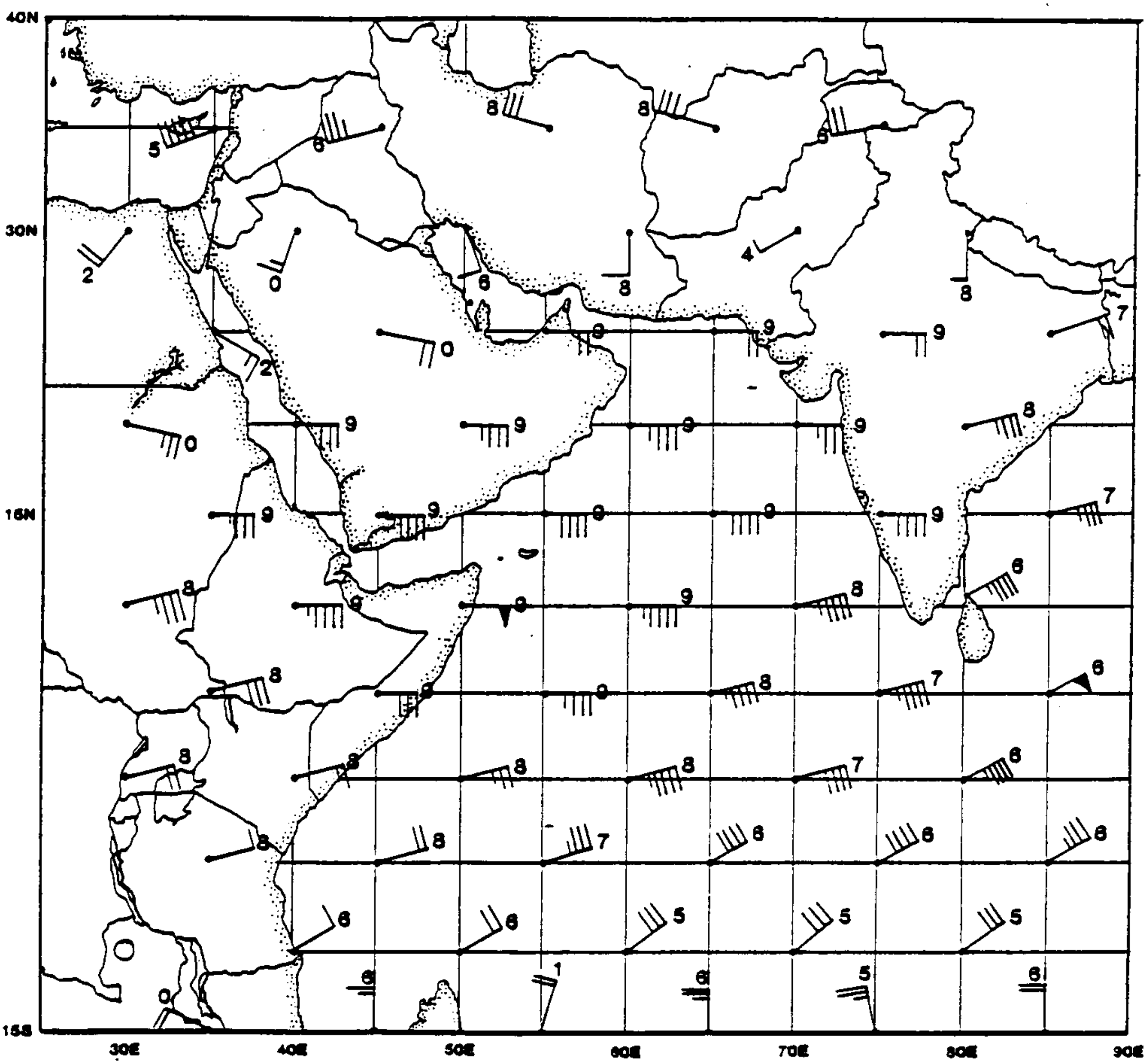


Figure 3-2b. Mean July 200 mb winds (adapted from Sadler, 1975). The numeral by each wind barb is the tens digit of direction. Note the speed maximum in the easterly winds along 10°N and the strong cross-equatorial flow south of India. The Easterly Jet "core" speeds are often stronger than shown because: (1) time averaging was used here, and (2) the jet "core" is usually found above 200 mb.

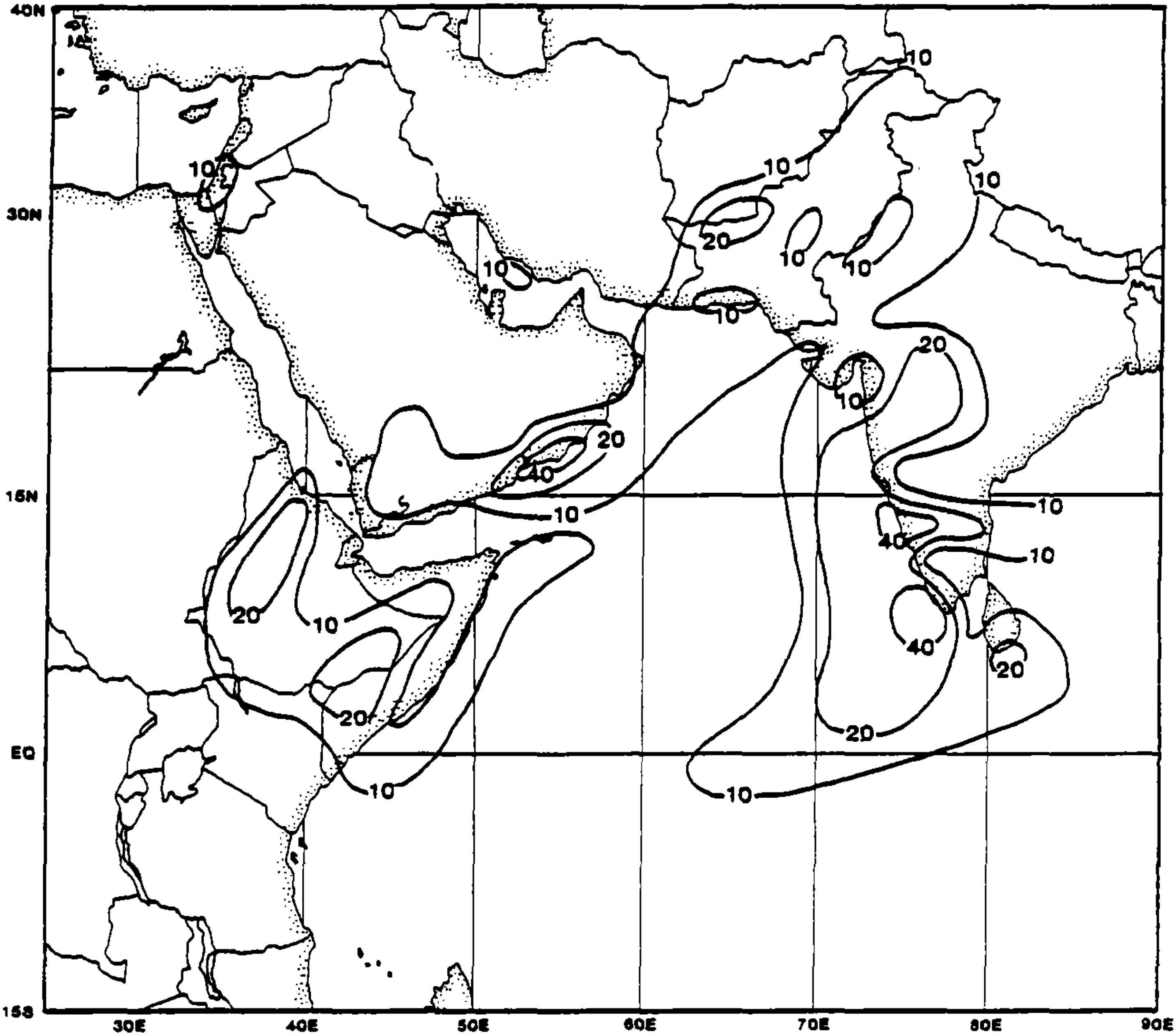


Figure 3-2c. Percent frequency of ceiling less than 1500 ft or visibility less than 3 n mi. Note that ceiling and visibility are infrequently restricted during the Southwest Monsoon except near shore over the central Arabian Coast and along the Indian Coast. Fog is rare; restrictions to visiblity are due to suspended dust (near Africa and Arabian Peninsula) or precipitation (Indian Coast). Low ceilings are primarily responsible for the contour maximum over the Arabian Coast and contribute to the maxima over the Indian Coast.

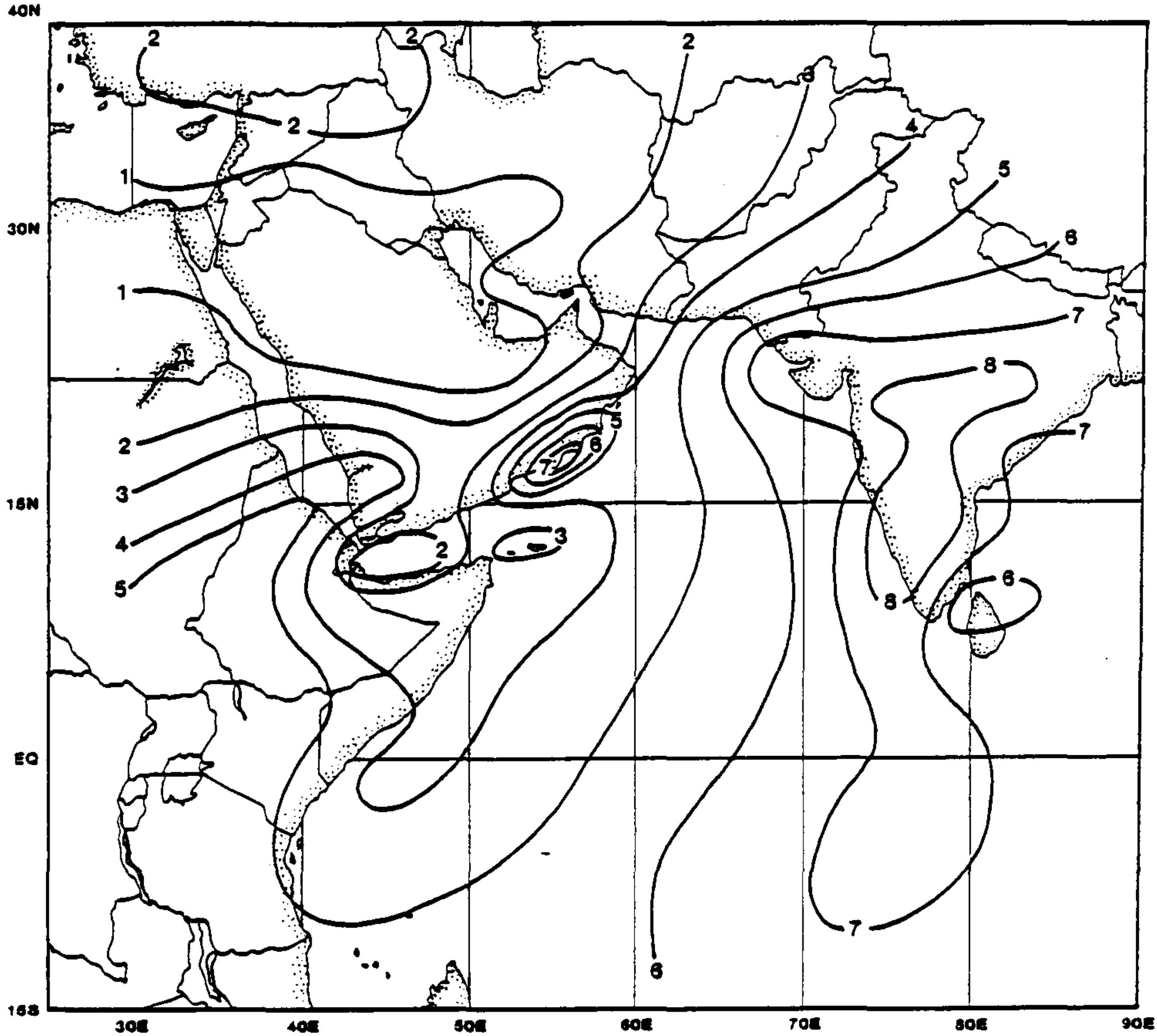


Figure 3-2d. Mean total cloud cover in tenths. The contour maximum over the Arabian Coast is due to persistent low stratus, particularly on the windward side of headlands and islands. The maximum over India is generally convective with considerable cirrus blow-off due to strong vertical wind shear. The relative maximum over the southern Red Sea is generally due to convective activity over neighboring terrain (see Figure 3-2e).

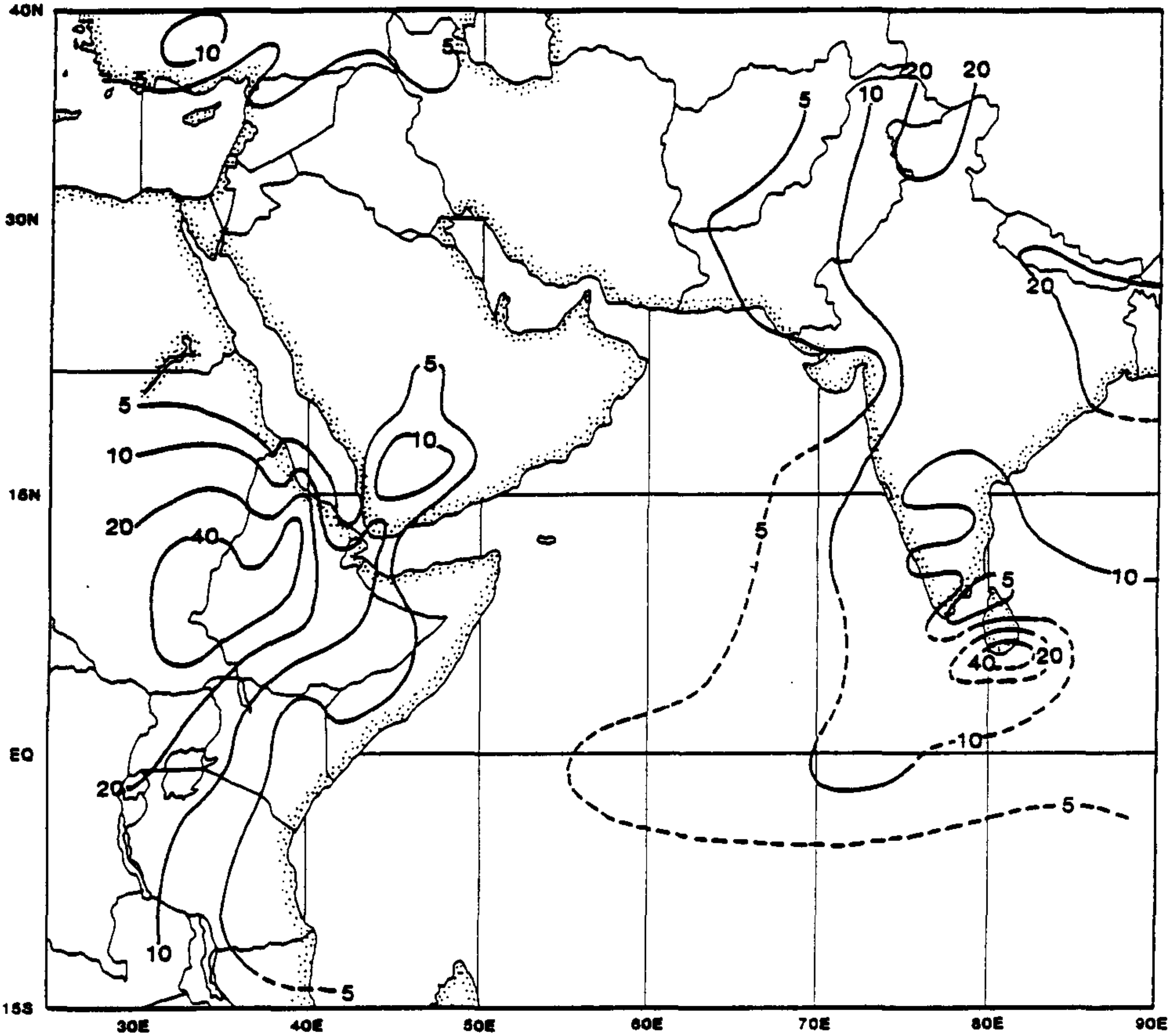


Figure 3-2e. Percent days with thunderstorms. Data for the Central Arabian Sea and the Indian Ocean area shown in the lower portion of the figure are very sparse. Dashed contours are estimates based on satellite imagery; solid contours are based on observations.

b. Monsoon Trough: ". . . the term . . . will be reserved for the intense trough of low pressure which occurs when the primary near-equatorial trough is displaced far to the north (e.g., over northern India and the northern part of the Bay of Bengal) and the Southwest Monsoon becomes well established . . ." (Cuming, 1973)

The preceding definitions tend to explain the characteristics of the sea level pressure pattern associated with each feature, i.e., an area of persistent low pressure. In our area of concern, the Heat Low and the Monsoon Trough are essentially coincident at the surface during the Southwest Monsoon. The differences between the two features occur in the middle and upper troposphere.

The temperature structure of the Heat Low (Thermal Low) over continents is such that the surface Heat Low is overlaid by higher pressure-heights on upper troposphere constant pressure charts used by Navy forecasters. On the other hand, the thermal structure of the Monsoon Trough is not necessarily symmetrical, usually resulting in a horizontal displacement with height of the trough axis. The slope of the trough with height separates (in the vertical) broad wind-flow areas which are nearly of opposite direction. The Monsoon Trough tends to follow the latitudinal migration of the sun's heating but often lags or leads due to terrain influences. Synoptic scale disturbances in the middle troposphere may lead to short-term oscillations of several degrees in the latitudinal position of the Monsoon Trough.

Figure 3-3 is a cross section through western India depicting zonal wind components. It clearly shows the spatial relationships between the low-level Southwest Monsoon, Easterly Jet, Monsoon Trough, Heat Low, Subtropical Ridge and the Extratropical Westerlies aloft.

3.2.3 "Onset" of the Southwest Monsoon

Although weak southwesterly winds may appear during the latter stages of the Spring Transition, the start of the real Southwest Monsoon is usually signalled by a "burst" in the cross-equatorial wind flow (from south to north) near the surface. This increase occurs abruptly, then spreads in an orderly sequence. As the region of strengthening winds expands and progresses northeastward across the Arabian Sea, an area of enhanced convective activity sweeps toward the west coast of India. Cyclonic shear on the northern edge of the "surge"often

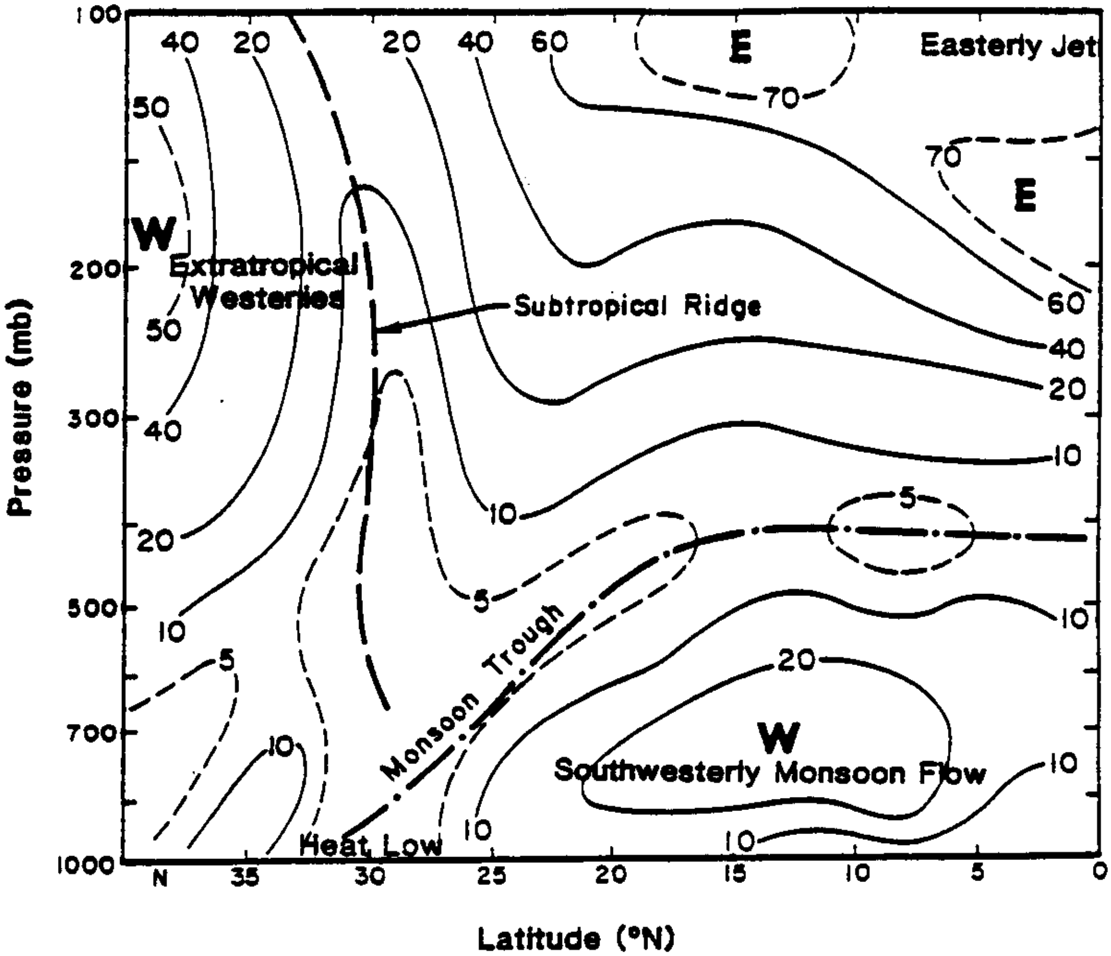


Figure 3-3. Cross section of the July resultant zonal wind speeds (kt) and directions (East or West) along western India showing the relationships among features discussed in the text (adapted from Miller and Keshavamurthy, 1978).

leads to formation of an "Onset Vortex". Satellite imagery of such a vortex is shown in Figure 3-4. The onset may occur at any time between mid-May and mid-June and is nearly always preceded by intensification of the Southeast Trades over the southern Indian Ocean.

"ONSET" FORECAST RULES/AIDS.

a. The sequential steps of the "burst" of the monsoon are:

(1) Increase in the strength of the southern hemisphere tradewinds.
(2) Strengthening of the cross-equatorial flow (see Section 3.3.1 for a description of the Somali Jet).
(3) Speed increase in the southwest flow off the northern African Coast (frequently accompanied by development of an area of enhanced convection).
(4) Formation and development of an "Onset Vortex".
(5) Sharp increase in the precipitation along the southern Indian Coast.
(6) Northward spreading of strong southwesterly flow to eventually cover all of the Arabian Sea.
(7) Establishment and strengthening of upper level easterlies.

b. Satellite imagery "clues":

(1) Low-level cloudiness parallel to the African Coast (off Somalia).
(2) Movement of a convective area or line northeastward across the Arabian Sea.
(3) The development of an "Onset Vortex".
(4) Movement of the "Onset Vortex" northward to about 20°N and then toward the Arabian Coast.
(5) Northward progression of convective clouds along the Indian Coast.

c. The time period from the increase in the Somali Jet to the arrival of the Southwest Monsoon over the southern Indian Coast is 3 to 4 days.

Figure 3-4. This DMSP visual image is typical of the "Onset Vortex" which signals the "burst" at the start of the Southwest Monsoon. These vortices (cyclonic storms) form in the Near-Equatorial Trough as it moves northward toward its mean position over India in this season. Maximum winds in this case reached 55 kt. Similar "Onset Vortices" have been identified in 37 of 68 seasons from 1901-1968. Low-level (cyclonically curved) cloudlines can be seen to the north and east of the center, and upper-level anticyclonic outflow is indicated by the cirrus cloud pattern. Heavy convection is occurring along the coast of India and over the ocean area southeast of the center. Notice that cirrus plumes from cumulonimbus buildups stream westward in response to the upper-level Easterly Jet. It is common for low-level southwesterly flow and upper-level Easterly Jet flow to develop rapidly in the wake of the "Onset Vortex". The approximate local sun time at the center of this image is 1100 (0627Z).

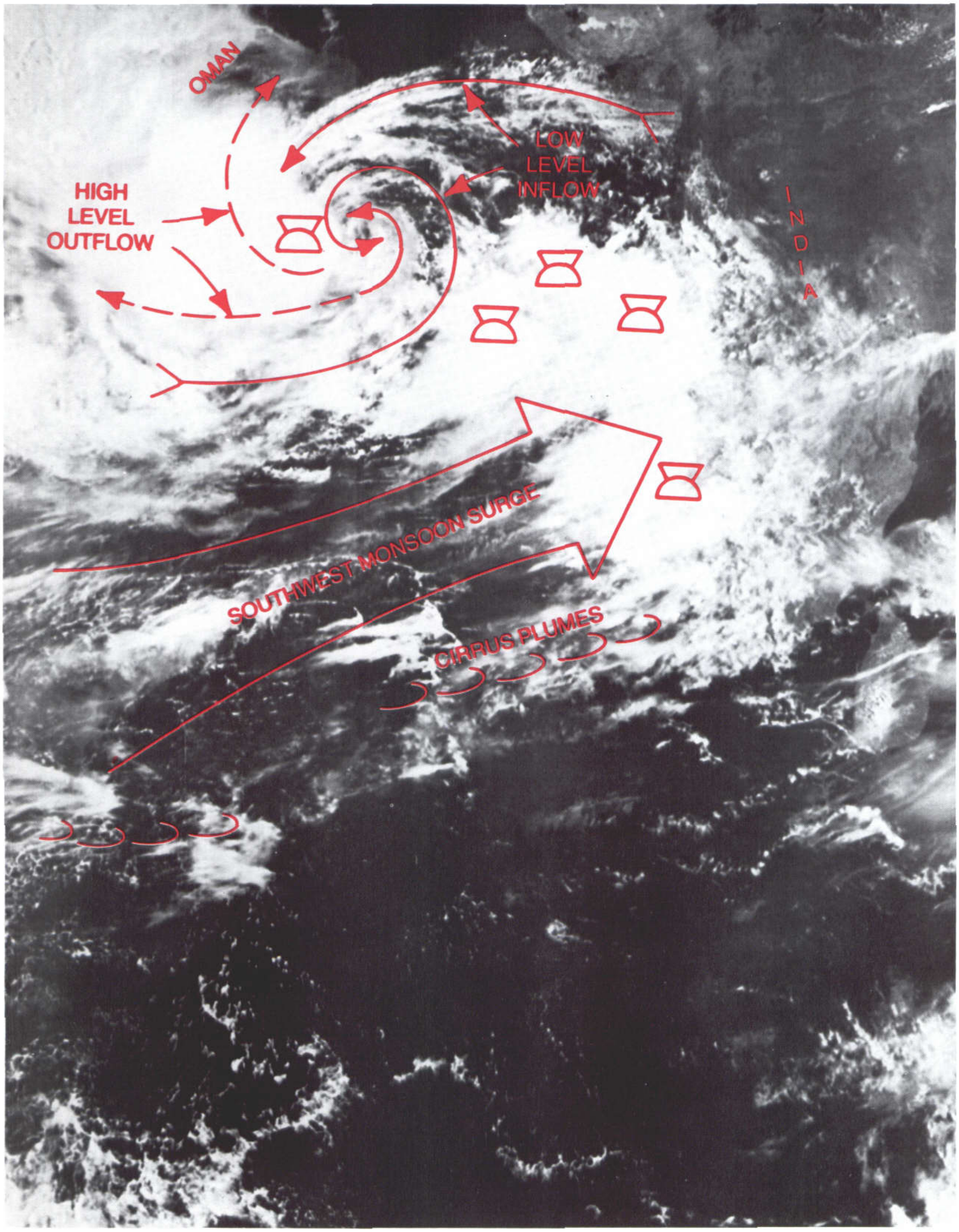


Figure 3-4. DMSP visual image of a mature "Onset Vortex" approaching the coast of the Arabian Peninsula (June 18, 1979).

3.2.4 Basic Southwest Monsoon Flow

The onset of the Southwest Monsoon was described in the previous section. Once the basic flow becomes established, there are two general types based generally on the total amount of cloud cover and the intensity of precipitation over western India. The two major categories are frequently referred to as: (a) "weak" monsoon flow and (b) "strong" monsoon flow. In both cases the total pressure gradient over the Arabian Sea is nearly the same; however, in "weak" situations the maximum gradient is found north of 23°N (mostly over land) and in "strong" situations it is found over water (usually 13°N to 21°N).

Figure 3-5 illustrates moderately "strong" flow during the Southwest Monsoon. This DMSP photo should be compared with the weaker flow depicted during the "Onset Vortex" stage shown in Figure 3-4. Note that the low-level clouds from the Gulf of Oman eastward to the Indian Coast indicate weaker winds here in the "strong" case. However, the clear area east of Socotra Island bounded on the east and north by cloud lines indicates an intense surface wind maximum. Limited data (Brody, 1977) indicate that the northern branch of the monsoon flow is displaced southward and intensified by mid-tropospheric disturbances during "strong" cases. The data also indicate deeper southwesterly flow over the Central Arabian Sea and Indian Coast in "strong" cases. Brody also concluded that the Subtropical Cyclones which influence the northern part of the Arabian Sea and occur in the upper-level Monsoon Trough between 700 and 500 mb are a major producer of clouds and rainfall along the northwest coast of India. These Monsoon Trough depressions frequently originate in the Bay of Bengal but influence monsoon intensity over India and the northern Arabian Sea. These upper circulations sometimes penetrate downward and become detectable at the surface but do not develop into classic tropical storms or hurricanes. Their surface reflections often affect the location of the maximum surface pressure gradient and therefore the strength of the low level winds.

Figure 3-6 is a DMSP visual image of a "strong" Southwest Monsoon situation when virtually all of the Arabian Sea is covered with clouds. This photo should be compared with Figures 3-4 and 3-5 to illustrate possible differences in overall intensity of monsoon flow during this season.

Figure 3-5. This DMSP image shows cloud cover which is typical of a "moderately strong" Southwest Monsoon flow situation. The relatively clear area just east of Socotra Island with diverging cloud lines to the east and north reflects the region of maximum low-level winds. The low level cloud lines clearly show the anticyclonic flow pattern in the Central Arabian Sea. The low-level wind direction is also apparent from heavier cloud formations on the windward slopes of Socotra Island and on headlands along the Arabian Coast. The absence of dense cirrus plumes over the Indian Coast suggests that vertical development is not excessive, and that rainfall may not yet be heavy. A light veil of dust can be seen over the Persian Gulf as greyish plumes; the dust appears to be heaviest near the Qatar Peninsula. The approximate local sun time at the center of this image is 1000 (0610Z).

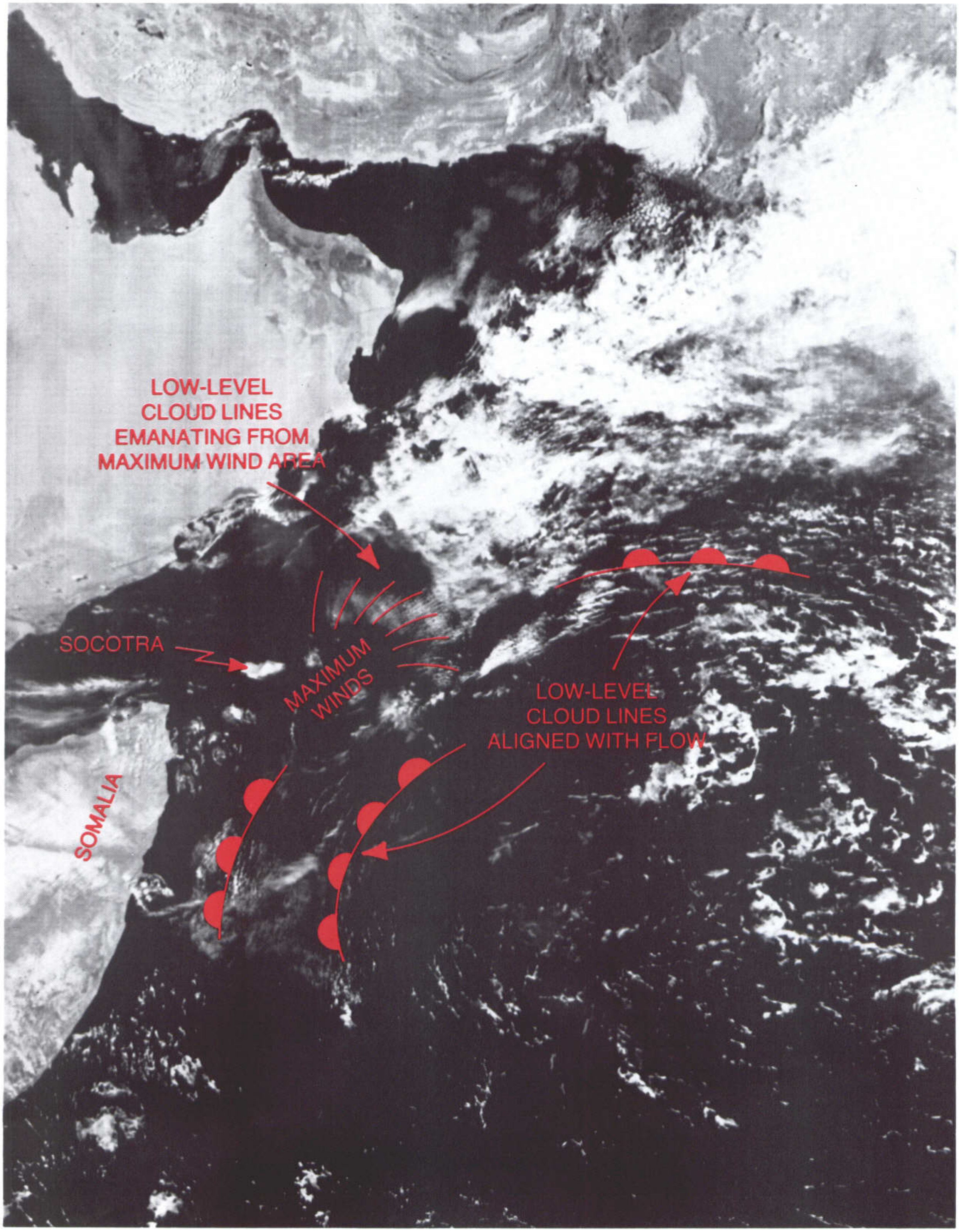


Figure 3-5. DMSP visual image of the Arabian Sea during a "moderately strong" Southwest Monsoon period (July 10, 1979).

GENERAL SOUTHWEST MONSOON FORECAST RULES/AIDS.

a. When the Somali Jet intensifies, the Southwest Monsoon flow over the Arabian Sea (and clouds/rain over western India) intensifies 1-2 days later.

b. When subtropical cyclones develop between 700 and 500 mb in the Monsoon Trough over the Bay of Bengal or the northern Indian Coast, forecast low-level wind flow to increase by 10-20 kt off the central Indian Coast — particularly if there is evidence of the cyclonic circulation penetrating downward.

c. If the maximum surface pressure gradient occurs north of 23°N (over land), forecast "weak" monsoon flow over the Arabian Sea with maximum winds near 2000 ft. If the maximum gradient is over water (13°N to 21°N), forecast "strong" monsoon flow conditions with maximum winds above 3500 ft.

d. During "strong" monsoon conditions, the area north of 22°N usually experiences relatively light surface winds.

3.2.5 "Breaks" in the Southwest Monsoon

"Breaks" in the Southwest Monsoon are the result of a breakdown in the entire monsoonal circulation pattern — including a weakening of the upper-level anticyclone over the Himalayas and the upper-level easterlies over our area of interest. Ramamurthy (1969) found that definite "breaks" in the Southwest Monsoon occurred during 68 out of a total of 80 years studied. The longest breaks last from 17-20 days, but the most frequent duration is 3-4 days. Such breaks are more common in August than in other Southwest Monsoon months. M. Murakami (1976), and Krishnamurti and Bhalme (1976) found a period of alternation between active and inactive monsoon spells of around 2 weeks.

FORECAST RULES/AIDS FOR "BREAKS" IN THE SOUTHWEST MONSOON.

a. "Breaks" do not occur when troughs in the mid-latitude westerlies (40°N-50°N) move unimpeded across the longitude belt 90°E to 120°E.

Figure 3-6. This DMSP image shows cloud cover which is typical of one of the "stronger" Southwest Monsoon situations. Most of the Arabian Sea is cloud-covered and the entire Indian Coast except the northernmost extremity is experiencing heavy convective activity. The low-level inversion (if it exists at all) must be weak because considerable vertical development is evident in several areas of the Arabian Sea. The cirrus plumes over the Central Arabian Sea indicate a diffluent upper-level flow pattern which is favorable for deep convective development. The 200 mb data (from MONEX) for the date support the directional divergence of the plumes although mean wind climatology does not reflect this pattern, indicating that it is transient. Notice that some low-level cloud lines can be seen in the lower-left portion of the image. The approximate local sun time at the center of this image is 1000 (0636Z).

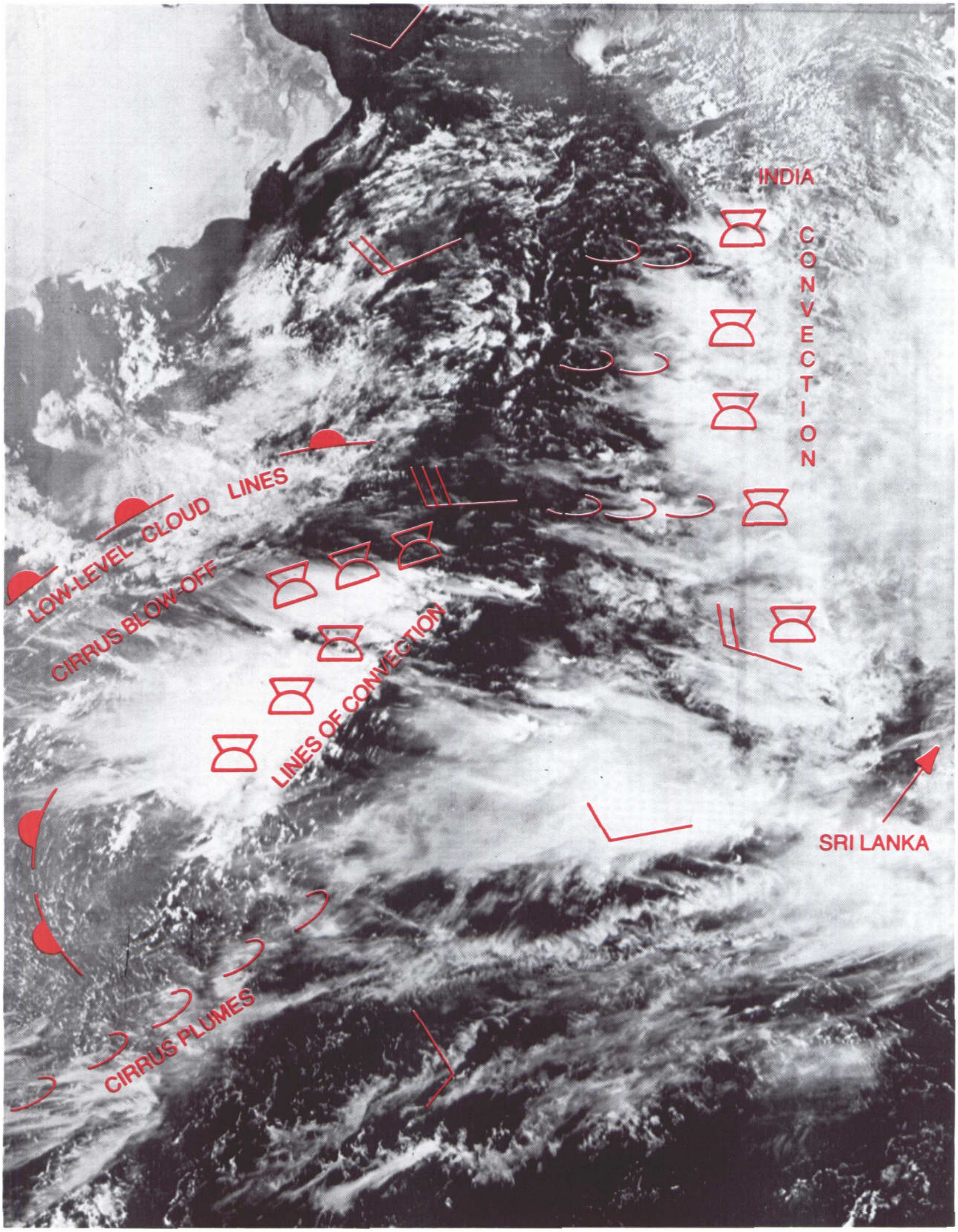


Figure 3-6. DMSP visual image of a "strong" Southwest Monsoon (June 23, 1979).

b. Regular development and movement of mid-troposphere monsoon depressions from the Bay of Bengal across India is not conducive to causing a "break" in the Southwest Monsoon.

c. Development of a blocking high between 35°N to 70°N and 90°E to 115°E is favorable for causing a "break" in the intensity of the Southwest Monsoon.

d. When a "break" starts to occur, forecast the rainfall belt normally near 20°N to be replaced by one near 25°N with a second belt near 7°N. Also forecast the upper-level easterlies to weaken (and shift northward) and the low-level southwesterlies to weaken with the northern branch of the Somali Jet becoming the stronger branch.

3.2.6 The Upper-Level Easterly Jet

The upper level Easterly Jet is an important large-scale aspect of the Southwest Monsoon. As pointed out earlier, its intensity is directly correlated to: (a) the intensity of the upper-level Himalayan anticyclone, (b) the occurrence and intensity of mid-tropospheric monsoon depressions and (c) the intensity of the low-level southwesterly flow over the Arabian Sea. This high tropospheric wind phenomenon is a persistent feature during the Southwest Monsoon. Due to the extremely high air temperatures above the continental heat lows, the pressure minimum decreases rapidly with height and becomes a pressure maximum above 500 mb. This maximum continues to intensify with altitude to the tropical tropopause, forming a strong anticyclone aloft. The strength and persistence of this upper-level feature result in relatively constant easterly winds in the upper troposphere and lower stratosphere over this area throughout the warm season. The mean position of the "Easterly Jet" is above 40,000 ft near 10°N (see Figure 3-7); however, some climatologies (e.g., Sadler, 1975) show a secondary maximum near the Equator in the Central Arabian Sea. Wind speeds over 100 kt have been observed. Fluctuations appear to be directly related to changes in the strength of the Southwest Monsoon flow, but quantitative (or causal) relationships have not been established. Recent investigations by Verma (1980) and Ramon, et al. (1980), suggest that anomalies in the upper-tropospheric westerly (mid-latitude) flow and the mean temperature in the Subtropical Ridge affect the strength of the monsoonal flow.

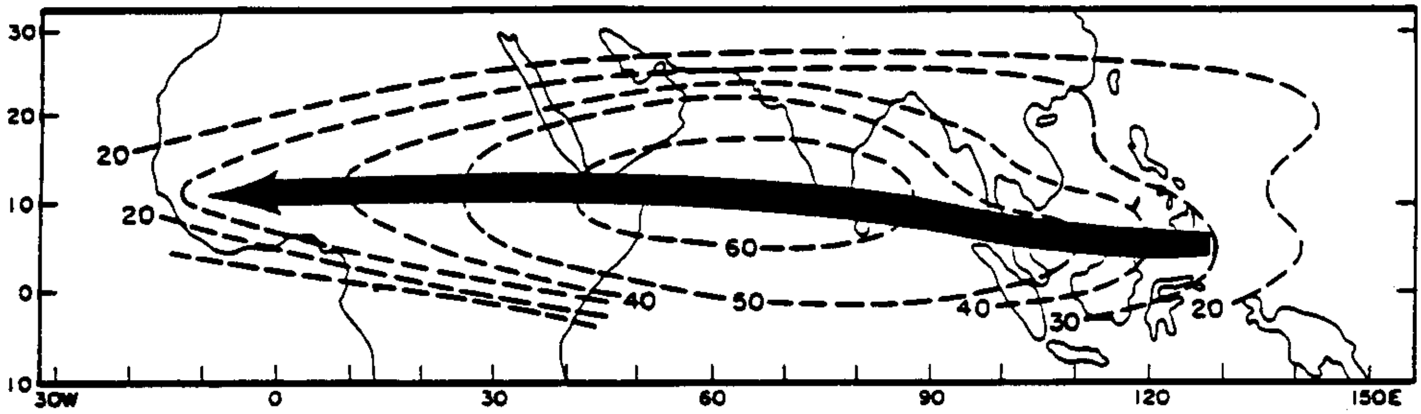


Figure 3-7. The upper-level Easterly Jet over the Asian-African area as illustrated by the resultant wind speeds (kt) at 150 mb during July-August (after Flohn, 1964).

3.3 Regional Features

3.3.1 Arabian Sea

During the Southwest Monsoon regime, weather and oceanographic conditions over the Arabian Sea are dominated by the strong, persistent flow over the area. Both low-level and high-level circulation features are quasi-permanent but exhibit fluctuations which are important. Large-scale aspects of the overall circulation and fluctuations therein were discussed above; this section focuses on wind and cloud conditions on the regional scale.

Low-Level Features

Low-Level Clouds. Two predominant types of low level clouds are found over the Arabian Sea during the Southwest Monsoon: (a) inversion - capped clouds and (b) convective clouds which break through the inversion. Figure 3-8 is typical of "weak" monsoon flow in this season. Note that there is a gradual downward slope of the inversion from east to west across the Arabian Sea. A similar section taken north-south through the Central Arabian Sea would show that the inversion also slopes downward from south to north. Although the inversion heights shown on the overlay are typical, the inversion tends to be higher and weaker during "strong" monsoon flow and lower and stronger during "weak" flow.

Low-Level Winds. During the summer monsoon, intense heat lows form over the desert areas surrounding the Arabian Sea. At the same time, high mountains to the north seal off the area from cold air outbreaks, and mountains over eastern Africa present a barrier to low-level wind flow. As a consequence of these radiational and topographic features, a strong southerly flow occurs along the African Coast and a broad southwesterly flow dominates the Arabian Sea. The southerly flow along the African Coast results in cold upwelling along the northern African Coast (off Somalia). The upwelled water cools the overlying air and produces a local high pressure ridge which intensifies the pressure gradient between the coastal area and the heat low over the inland area. An additional effect of the upwelling is to produce a thermal wind component which increases vertical wind shear in the lower levels. All of these factors contribute to the formation and maintenance of a strong, relatively narrow wind stream (Somali Jet) along the African Coast and a broad, persistent flow (Southwest Monsoon) over the Arabian Sea and its coastal areas.

Somali Low-Level Jetstream. The "Somali Jet", as defined above, occurs from April through October and is one of the strongest and most sustained low-level wind systems on earth. It is normally strongest in July and August when maximum speeds up to 100 kt have been observed. The core is usually centered at an elevation of about 5000 ft. Figure 3-9 shows a monthly mean airflow chart at 3500 ft for July. Notice the local speed maxima north of Madagasgar, off the coast of Kenya and to the northeast of Socotra Island. These are semi-permanent low-level wind features during the Southwest Monsoon. Figure 3-5 showed a satellite view of the Arabian Sea when the Somali Jet and the Southwest Monsoon wind flow were both relatively intense. The low-level wind speed maximum just east of Socotra Island usually appears as a relatively clear area bounded on the north and east by diverging cloud lines. When the Somali Jet is well developed, the Somali coastal area is usually characterized by clear skies; the clear area correlates well with cold upwelling shown by satellite IR data (see Figure 7-2).

Figure 3-8. This DMSP image shows detailed cloud structure over the Arabian Sea during a relatively "weak" Southwest Monsoon situation (see Section 3.2.4 for further discussion). This case was selected to illustrate variations in the strength and height of the low-level inversion during "weak" flow. The inversion is lowest near the African and Arabian coasts and slopes upward toward the east and south. In particular, note the increase in density and brightness of the clouds south and east from the Gulf of Aden. The "wave-like" clouds in the Central Arabian Sea are thought to be the result of gravity waves on the inversion interface. The convective clouds and related cirrus cloud plumes near the central Indian Coast indicate that the inversion is weak or non-existent there. During periods of "weak" Southwest Monsoon flow the low-level winds and cloudiness over the northern Indian Coast usually increase. The cloudiness seen in this image is typical of a "weak" condition. The approximate local sun time at the center of this image is 1030 (0604Z).

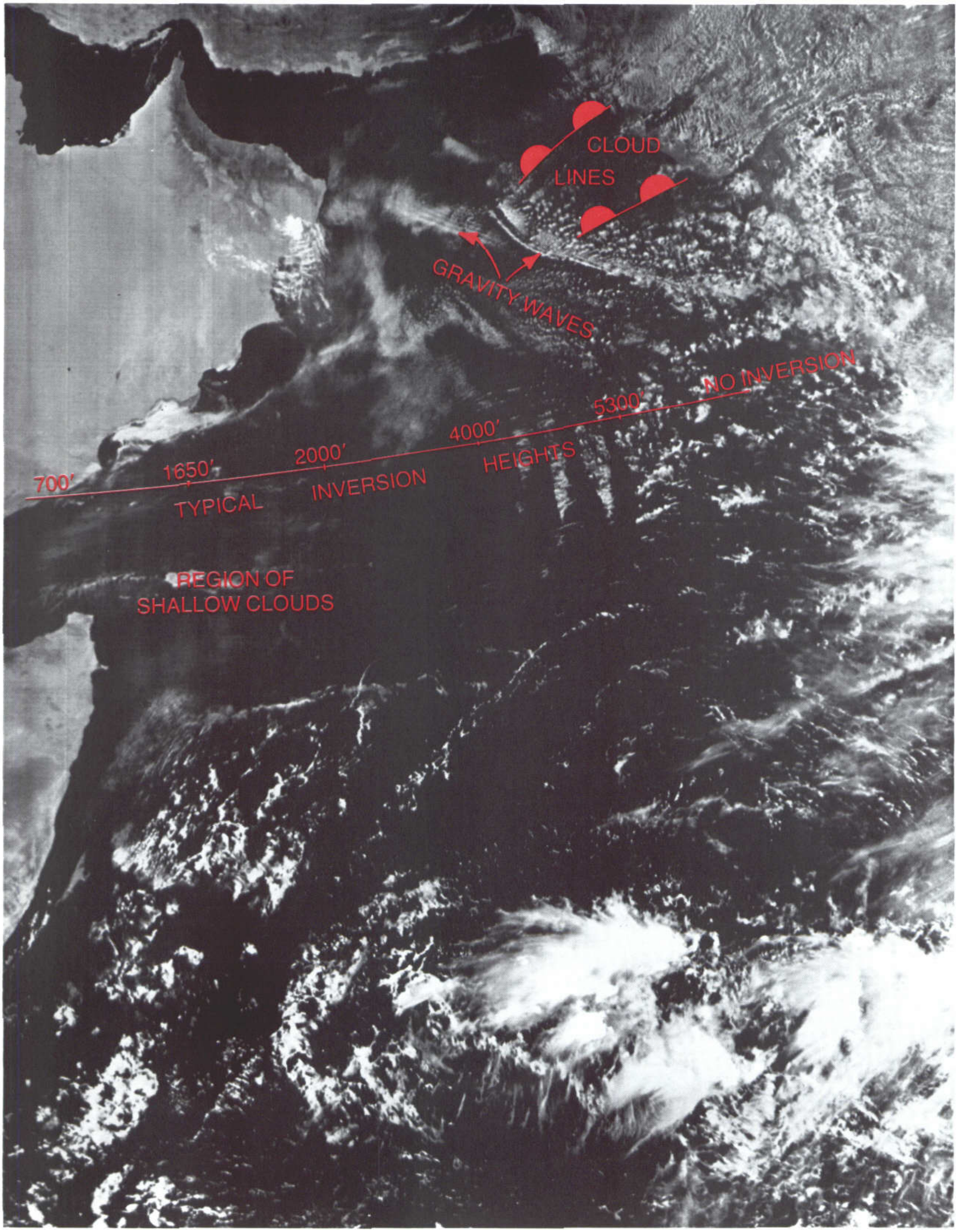


Figure 3-8. DMSP visual image for July 5, 1979 showing detailed cloud structure over the Arabian Sea.

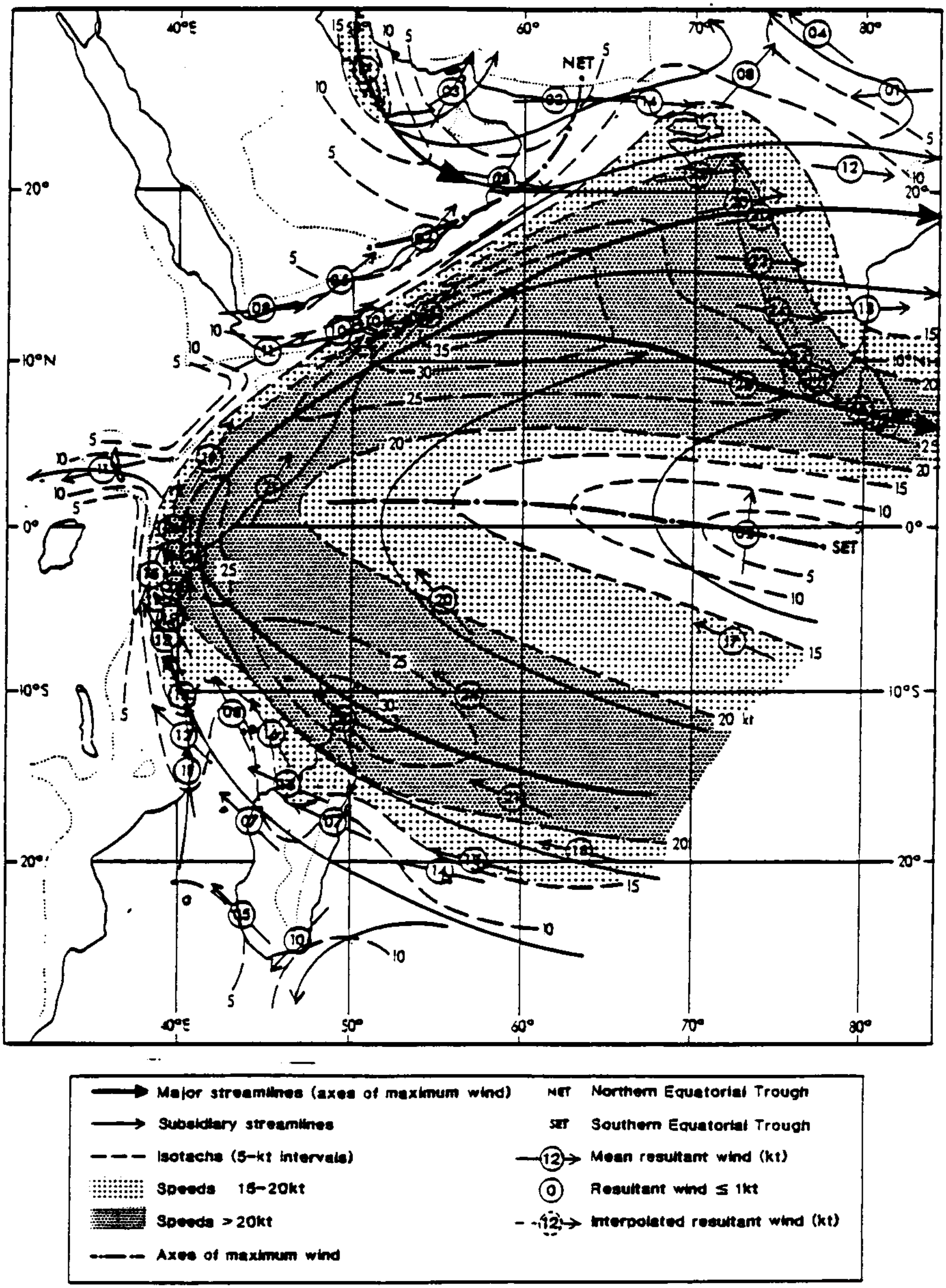


Figure 3-9. Mean July winds near 3,500 ft (adapted from Findlater, 1971).

"SOMALI JET" FORECAST RULES/AIDS.

a. In the absence of observations, forecast core speeds of 50-65 kt at an elevation of 5000 ft along the climatic jet axis shown in Figure 3-9. (Note: Multiple cores (jetlets) are possible.)

b. Fluctuations in core wind speed are associated with southern hemisphere cold-air outbreaks (i.e., strong migratory high pressure cells). Major fluctuations can be expected every 2-3 weeks. Core speeds of 65-80 kt are typical during intensification while speeds of 30-45 kt are most common during lulls.

c. Somali Low-Level Jetstream winds do not significantly impact air operations above 10000-15000 ft. (See other sections for discussion of high-level jetstreams.)

Upper-level Clouds. Much of the Arabian Sea is characterized by subsidence in the middle troposphere. This tends to suppress upper-level cloudiness. An exception to this rule occurs near the Indian Coast where convergence in the low- and mid-level flow causes copious rainfall and considerable convective activity. The High-Level Easterly Jet spreads the moisture which is carried aloft by this convection downstream (westward) over the Arabian Sea. The result is frequently a dense cirrus shield which is dissipating due to subsidence (high-level cloudiness therefore decreases westward). The amount/density of the cirrus deck is generally related to the intensity of the rainfall over western India. Figure 3-6 clearly showed the cirrus shield dissipating as it was being blown westward by the high-level flow.

CLOUD AND WIND FORECAST RULES/AIDS.

a. Density and westward extent of cirrus over the Arabian Sea is directly related to the intensity of monsoon rains over India. In "strong" monsoon flow, cloud cover extends 500-700 n mi to sea off India.

b. The African Coast, particularly in the north where upwelling is strongest, is nearly cloud-free during the Southwest Monsoon.

c. Distinct, closely-spaced cloud lines indicate relatively strong low-level winds.

d. Cloud patterns over the Arabian Sea and coastal areas provide the following information on inversion height:

(1) Cloud free except for stratus -- the inversion is near the surface.

(2) Continuous cloud line or wave pattern -- a strong low to medium level inversion exists (cloud-top temperatures from IR imagery would indicate relative height).

(3) Convective clouds -- the inversion is weak or non-existent.

e. The inversion (where it exists) is generally higher (lower) during "strong" ("weak") monsoon conditions.

Equatorial Cloud and Wind Patterns

The equatorial convergences typical of other tropical areas are not as well developed in the Indian Ocean during summer, hence cloudiness along the equator is somewhat less than in other tropical oceans. Cloudiness is suppressed by subsidence near the African Coast but is enhanced near Sri Lanka due to stronger convective activity; therefore, mean coverage (particularly of high clouds) increases from west to east.

From June through September, surface pressures in the southern hemisphere subtropical ridge are relatively high while those in the Middle East heat trough are at their annual low. The result is a unique wind flow pattern over the tropical Indian Ocean. The Southeast Trades of the Southern Hemisphere veer across the Equator to become the Southwest Monsoon in the Arabian Sea with no doldrum area near the Equator itself. This pattern is relatively steady, but short-period speed fluctuations occur. Climatologically, the southern hemisphere Southeast Trades peak in June while the Southwest Monsoon winds are strongest in July.

Near the African coast, wind speeds increase from south to north as the Somali Jet crosses the Equator. Further eastward, the flow weakens considerably such that a speed minimum is found near the Equator at about 70°E, and winds are generally light and variable along the Equator east of 70°E.

Visibility Restrictions

In general, visibilities over the Arabian Sea and surrounding land areas are lower during the Southwest Monsoon than during the Northeast Monsoon. The following paragraphs discuss the causes for this deterioration.

Dust. The southern portion of the Arabian Peninsula, the coastal areas of the Red Sea and the Persian Gulf and the horn of Africa (Somalia) contain areas from which dust may be carried aloft by the prevailing winds during the Southwest Monsoon. Therefore, coastal areas (African and Arabian Coasts, Gulf of Aden) are frequently affected by dust haze. It is most common from mid-June to mid-August in this area. Occasionally the Gulf of Oman and the Makran Coast will experience dust haze from local sources, but this is usually limited to the period immediately preceding the onset of the Southwest Monsoon in the area.

Salt Haze. The combination of strong surface winds and low-tropospheric stability causes persistent salt haze over most of the Arabian Sea. Surface visibilities generally range 5-8 n mi, depending on wind speed and inversion height. In the northern and western coastal areas where salt haze and dust haze often occur together, lower visibilities are common.

Fog. Although atmospheric conditions are not conducive to the formation of dense fog, the sharp reduction of SST in coastal areas of the northwestern Arabian Sea causes moisture saturation in a shallow layer and contributes to poor visibility. The areas most often affected by lowered visibility or stratus are the windward shores of Socotra and the Arabian Coast between Riyan and Masirah Island. The period of occurrence and intensity is governed by the characteristics of the Southwest Monsoon (which causes the upwelling). The area near Salalah is particularly susceptible to low ceilings and visibilities; July and August observations at Salalah indicate that 60% of the reported visibilities are less than two miles.

Rain. Although salt haze (and occasionally, dust) occurs in the eastern portion of the Arabian Sea, the principal visibility restriction is rainfall occurring during monsoon surges and convective showers. Visibility less than a half-mile is frequently observed for brief periods.

VISIBILITY FORECAST RULES/AIDS.

a. In coastal areas, visibility usually reaches a minimum around 0600 local time and a maximum near mid-day.
b. Horizontal visibility over the Arabian Sea is generally reduced to 5-8 n mi in salt haze. (Dust near the Arabian Peninsula will cause additional restrictions but this varies with time and location.)

Tropical Cyclones

Except during early June, tropical cyclones are rare in the Arabian Sea (and South Indian Ocean) during this period. Past records indicate an average frequency of occurrence of about once every five years for cyclones to reach storm intensity. Of those that occur, most are located in the northeastern portion of the Arabian Sea, have tracks generally paralleling the west coast of India, and dissipate or make landfall east of 60°E. There are no cases on record of a tropical cyclone with maximum wind speeds of 34 kt or greater entering the Gulf of Oman or the Gulf of Aden.

TROPICAL CYCLONE FORECAST RULES/AIDS.

a. Conditions necessary for the formation of a tropical cyclone are:

   (1) Pressure trough over the Arabian Sea north of 5°N
   (2) Weak vertical wind shear
   (3) Existing low-level disturbance
   (4) Upper tropospheric outflow

b. Watch for the formation of a surface circulation near the Indian Coast following the first surge in the low-level cross-equatorial flow and then watch for development in the enhanced convective area ahead of the surge in the Southwest Monsoon.

c. Normal movement of the "Onset" tropical cyclone is north along the Indian Coast, then curving westward toward the Arabian Coast. The strongest peripheral surface winds are typically found southeast of the surface circulation center.

3.3.2 Red Sea and Gulf of Aden

Large-scale circulation features associated with the Southwest Monsoon were addressed in Section 3.2. Over the Red Sea and Gulf of Aden, fluctuations are less pronounced and much of the variability is due to diurnal and terrain effects.

Low-Level Features

Low Level Clouds. The Red Sea is relatively cloudless during this season, particularly in the northern part (See Figure 3-10). When clouds occur, afternoon cumulus predominate with bases mostly between 2,000 and 5,000 ft MSL. The area south of 15°N and west of 45°E experiences the greatest cloud coverage; however, clouds seldom affect naval operations anywhere in this area. When early morning low cloudiness exists in the Gulf of Aden, it usually dissipates by noon.

CLOUDINESS FORECAST RULES/AIDS.

a. In the Gulf of Aden, morning low cloudiness decreases sharply between 0800 and 1200 local time.

Low-Level Winds. The semi-permanent low pressure systems over land and the terrain bordering the Red Sea cause extremely persistent winds from the northwest quadrant. In the Gulf of Aden, these same influences result in winds from the southwest quadrant. Wind speeds are usually less than 28 kt but occasionally exceed 28 kt near the northern end of the Red Sea and may reach gale force near the southern shore of the Gulf of Aden. In general, the wind direction is parallel to the long axis of both water areas. Near shore, the direction is usually affected by diurnal (land/sea breeze) forces which add an onshore component during the daytime and an offshore component at night. If the local terrain causes the diurnal influence to oppose/reinforce the gradient wind, significant speed variations can occur; for example, the additive effects can result in local wind maxima in the morning and minima in the afternoon. The southwest coast of the Gulf of Aden (Berbera) provides an example of this phenomenon.

Upper-Level Features

High Clouds. High clouds seldom occur over the northern two-thirds of the Red Sea in summer due to subsidence; however, the southern extremities of the Red Sea and the Gulf of Aden occasionally experience cirrus blow-off from thunderstorms or heavy monsoon storms in the eastern Arabian Sea. The latter effect is most likely to occur in July when the monsoon flow is most intense.

Upper Winds. The slope of the Monsoon Trough from a surface position over the Arabian Peninsula to a middle troposphere position over the horn of Africa (see Figure 3-3) results in a veering of the wind direction with height over the Gulf of Aden. The combination of terrain influences and low-level pressure gradient also produces a veering of wind direction with height over the Red Sea. Above about 20,000 ft, a broad band of easterly winds extends from about 30°N well into the Southern Hemisphere. The mean position of the axis of maximum wind speeds in the upper-level Easterly Jet is directly over the Gulf of Aden at altitudes in excess of 40,000 ft. Maximum jet core speeds over 100 kt have been observed; however, in July over the Gulf of Aden they average about 65 kt. Variations in the wind direction of the Easterly Jet are small throughout the monsoon period but significant speed changes occur. These changes appear to be directly related to the strength of the low-level Southwest Monsoon flow.

Figure 3-10. DMSP photo showing typical cloud cover over the Red Sea and Gulf of Aden during the Southwest Monsoon. This case occurred at the beginning of the season and the "Onset Vortex" can be seen at the right edge of the picture. A meso-scale dust storm is occurring just south of Port Sudan and a thin veil of dust can be seen downwind from the main plume (southwestern portion of the Red Sea). Notice that except for the high-level cirrus blow-off from the "Onset Vortex", the Red Sea, Gulf of Aden (and Persian Gulf) are nearly cloud free. Clouds indicate that precipitation is likely along the Arabian Coast from Salalah to Masirah. The approximate local sun time at the center of this image is 1100 (0750Z).

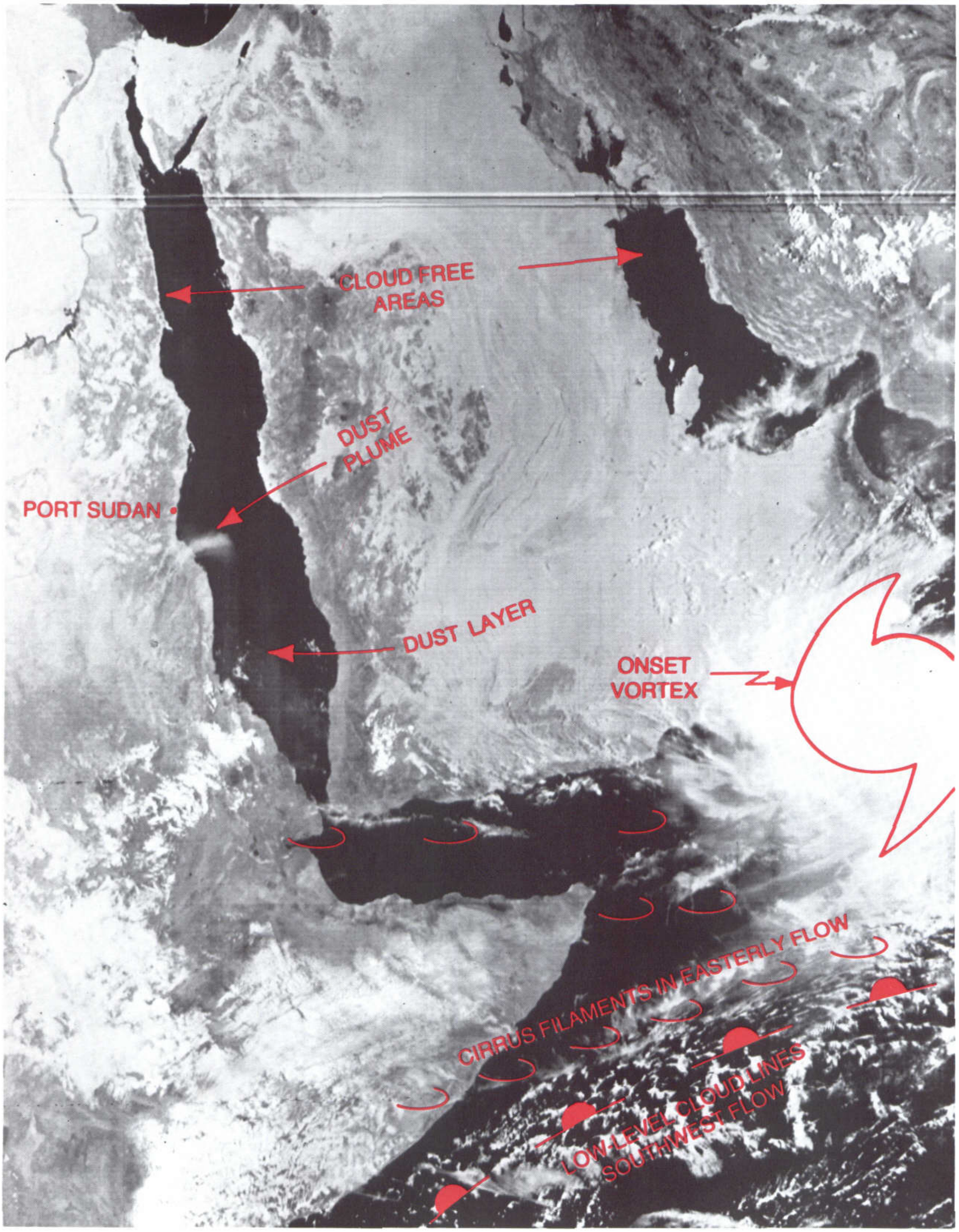


Figure 3-10. DMSP visual image recorded near local noon on June 19, 1979 showing typical cloud cover over the Red Sea/Gulf of Aden during the Southwest Monsoon.

Visibility Restrictions

Dust and Sand. The northern Red Sea experiences its best visibility during the summer monsoon. Dust storms are relatively infrequent. The only area where the visibility decreases to less than 5 n mi more than occasionally is near the Gulf of Aqaba. In the area, visibility below 2 mi occurs about 5% of the time due to the localized winds caused by funneling.

Poor visibility is more frequent in the central and southern Red Sea; visibility below 5 n mi is experienced 10% to 30% of the time in July. Reductions to 1/2 n mi or less occasionally occur near terrain features which tend to funnel local winds (see the area near Port Sudan in Figure 3-10). In most cases, the lowest visibility occurs in the early morning hours; however, poor visibility may also coincide with the most unstable period (usually in the afternoon) if terrain influences predominate.

The summer season is bad for visibility in the Gulf of Aden. Seaward of the effects of local terrain, visibilities below 5 n mi reach a maximum frequency of about 15% percent in July. In general, low visibilities are more frequent near shore. For example, less than 5 n mi visibility is recorded at Aden and Bender Cassim about 30% of the time. Figure 3-11 is a visual image of a large-scale dust storm. The milky appearance of the Red Sea, Gulf of Aden and Arabian Coast results from dust carried to considerable altitude by vertical mixing in the strong wind flow over the Arabian Peninsula. Normally, low-level restrictions to visibility are due to a dust haze which results from these storms. It is not uncommon, however, for mesoscale dust storms and occasionally sand storms to occur along the shores of the Gulf of Aden and the southern Red Sea. These storms generally travel from land toward the water and most often occur in the evening. They are often (but not always) associated with convective cloud cells. During brief periods, the visibility may be reduced to near zero, but rapid improvement in visibility is usually experienced after the wind subsides.

Fog. Fog seldom occurs during this season except in the immediate vicinity of Cape Guardafui.

Figure 3-11. DMSP image of a large-scale dust storm over the southern Red Sea and the Gulf of Oman. This dust cloud originated in the area northwest of the Persian Gulf more than a day earlier. The thickest portion of the dust cloud, which is crossing the coast just west of Aden, extends upward to mid-tropospheric altitudes. (IR image, not shown, indicates brightness equal to that of nearby convective clouds.) Variation in the grey shades along the eastern shore of the Red Sea indicates the effects of local terrain on the dust density. The anomalous dark area just north of the Bab al Mandab is downwind from a small convective cloud mass; it may be caused by downdrafts from showers over the mountains. Low-level cloud lines in the central portion of the figure and the convective activity along the right border indicate a relatively "strong" monsoon condition. Notice that the symbols on the overlay for this image represent the surface winds from actual observations as well as the location of stations reporting dust or haze. The approximate local sun time at the center of this image is 1100 (0722Z).

Figure 3-11. DMSP visual image of a large scale dust storm affecting the Gulf of Aden and the southern Red Sea on June 26, 1979.

Precipitation. Visibility restrictions due to precipitation occasionally occur in thunderstorms, but the most serious restriction to visibility is dust rather than rainfall.

VISIBILITY FORECAST RULES/AIDS.

a. Normally, the critical wind speed for raising dust is about 15 kt and for raising sand, about 20 kt. Recent rainfall raises these thresholds and vehicular traffic (e.g., military exercises) lowers them. Regardless of moisture content, greater than normal quantities of particulate material will become airborne at a given wind speed if the surface has been disturbed by heavy traffic.

b. Dust storms are most common in the late afternoon or evening when the atmosphere is most unstable. Exceptions to this general rule occur where the land breeze component opposes/reinforces a strong pressure gradient, (e.g., an early morning maximum at Berbera), or as a result of noctural thunderstorms.

c. Mesoscale dust storms which result from convective activity tend to occur more often on days during which general wind flow is lighter than normal.

d. The first indication of a dust storm is an apparent low cloud on the horizon which appears to be approaching. Often it will consist solely of a low, brown dust cloud. Usually the surface dust/sand cloud will not reach a given point until after the leading edge of the cloud aloft has passed over the point.

e. Air to ground visibility is much less than horizontal visibility in the presence of dust, due to the scattering effect on sunlight.

f. Suspended dust is depicted on satellite visual imagery as a hazy veil. IR brightness is an indicator of the altitude (temperature) of the dust cloud, but is rather inaccurate due to the effect of the warm surface radiation which partially penetrates the dust cloud.

g. When strong dust storms are being reported around the northern end of the Persian Gulf, forecast dust haze one to two days later over the Gulf of Aden and southern Red Sea.

h. The development of large convective cells over coastal ranges increases the probability of local dust/sand storms that evening.

Oceanographic Features

Thermal Structure. The geography of the Red Sea results in an unusual thermal structure. Strong insolation throughout the year keeps the Sea Surface Temperature (SST) above 25°C except in the extreme northern part where it occasionally drops below 22°C during the winter. Since this water is highly saline, it sinks to form the bottom water of the entire basin. The temperature of this deep water is confined to a range between 21.5°C and 22.0°C. The maximum surface temperature occurs in the southern Red Sea where SST reaches about 32.0°C. The vertical temperature variation thus ranges from zero in the north during winter to about 10°C in the south during the summer. The mixed layer ranges from about 300 ft in the winter to less than 100 ft at the beginning of the summer monsoon. Since the sill depth at Bab al Mandab is about 300 ft, the deep water is unusually homogeneous.

The thermal structure of the Gulf of Aden is similar to that of the Arabian Sea except very near Bab al Mandab where high-density water flows out of the Red Sea at sill depth and descends the slope to a depth of nearly 5000 ft. This water is very warm and causes the 15°C isotherm to be depressed to a depth of more than 3000 ft creating near isothermal conditions between depths of about 600 ft and 4000 ft. Considerable cold water upwelling occurs near the entrance to the Gulf of Aden and to a lesser degree, along its northern shore during the Southwest Monsoon. Figures 7-1c and 7-1d show mean vertical temperature profiles from the Gulf of Aden and the southern Red Sea respectively.

Salinity. Since there is no significant inflow of fresh water and very little rainfall, the Red Sea has a negative water budget; therefore, the salinity is extremely high. The water deficit is made up by a net inflow through the Strait of Bab al Mandab, causing salinity to be lowest near the surface. Below the sill depth, salinity exceeds 40 o/oo everywhere and generally increases toward the north at all depths. A small amount of outflow occurs over the sill resulting in highly saline water on the shelf in the Gulf of Aden. Except for this localized phenomenon, Gulf of Aden salinity is typical of the Arabian Sea where excess evaporation causes salinity to be highest at the surface. Forecasters should expect anomalous underwater sound propagation due to the unusual thermal/salinity structure here.

3.3.3 Persian Gulf and Gulf of Oman

The strong, semi-permanent low-pressure system which persists northeast of this area is the controlling factor of the weather pattern during the summer monsoon period. Local diurnal effects are of secondary importance. Occasionally, subtropical cyclones, which are most intense in the middle troposphere, migrate westward from India and affect the Gulf of Oman during dissipation stages. Figure 3-10 presented an excellent, early-season satellite view of the area.

Low-Level Features

Low-Level Clouds. The Persian Gulf is virtually cloudless during the summer. From the Straits of Hormuz the mean cloudiness increases toward the southeast and also with the season from June to August. In the vicinity of Jiwani, Pakistan, broken to overcast clouds occur nearly half the time in August. Ceilings are below 1500 ft about 15% of the time, but the clouds tend to dissipate during the day, so that afternoon amounts are usually less than half those observed in the morning.

Low-Level Winds. The surface wind flow over the Persian Gulf and Gulf of Oman is controlled by two basic air currents. One flows from the northwest parallel to the long axis of the Persian Gulf; the other is an extension of the broader Southwest Monsoon flow of the Arabian Sea. Both currents are persistent -- particularly in direction. The Gulf of Oman up to the Strait of Hormuz is normally the transition zone between these two currents. The results are northwesterly winds over the Persian Gulf, south to southwesterly winds near the entrance to the Gulf of Oman and variable winds in between. The western approach to the Strait of Hormuz is usually characterized by southwesterly winds due to funneling. Local areas are susceptible to diurnal and terrain effects.

The Summer Shamal. From early June to mid-July, the Persian Gulf experiences what is known as the "Summer Shamal" or the "40-day Shamal". Winds blow steadily from the northwest with few, if any, breaks. The heat low over Pakistan, a trough to the lee of the Zagros Mountains, a semi-permanent high cell over northern Saudi Arabia and local terrain combine to create an enhancement of the low-level flow along the southwest shore of the Persian Gulf — particularly below 5000 ft.

At the surface, this "Summer Shamal" is often strong enough during the day time to cause numerous dust storms over southern Iraq and northwestern Saudi Arabia. The wind speeds decrease at night at the surface but do not decrease aloft. During the night under clear desert skies, radiational cooling causes a strong low-level inversion. The result is a very dangerous, "nocturnal jet stream" with its core located only 1000-2000 ft above the ground. Wind speeds in excess of 50 kt have repeatedly been observed at 1000 ft over Bahrain with the most probable time of occurrence being between midnight and dawn (surface winds at the time are usually less than 20 kt). Because of the potential threat of this phenomenon to Navy aircraft attempting to land at Persian Gulf airfields, a forecasting nomogram developed by Membery (1983) is reproduced in Section 7.4 dealing with Carrier Air Operations.

WIND FORECASTING RULES/AIDS.

a. Wind speeds in the Persian Gulf vary with the strength of the low pressure center and generally change gradually from day to day.
b. When gradient-level winds are 25 kt or more from the north or northwest, expect blowing dust to occur about mid-day if the surface inversion is destroyed by heating.
c. During the "Summer Shamal" expect a strong, low-level, "nocturnal jet" (midnight to dawn) to occur on clear, stable nights along the southern shore of the Persian Gulf. Winds at 1000 ft exceed 50 kt while surface winds are less than 20 kt (see Section 7.4 for forecast nomogram.)

Upper Level Features

The Monsoon Trough slopes sharply southeastward with height from a surface position near the Strait of Hormuz to a position over Bombay at the 500 mb level. The upper-level subtropical ridge extends eastward and west southwestward from a position near the northern end of the Persian Gulf.

High Clouds. Except over the northern Persian Gulf where summer clouds are rare, high clouds reach a secondary maximum during July and August. Generally these clouds consist of cirrus blow-off from monsoon disturbances occurring near the northwestern Indian Coast.

Upper Winds. North of the Monsoon Trough, winds generally veer from northwesterly to easterly with height. Near the northern end of the Persian Gulf, winds generally persist from the northwesterly quadrant below the 500 mb level. These winds are related to the Shamal and are strongest (up to 40 kt) at the lower levels (about 3,000 ft), then decrease with height.

Visibility Restrictions

Dust and Sand. In the northern two-thirds of the Persian Gulf, visibility reaches a minimum with the onset of the "40-day Shamal" in June. For example, Bahrain drops from well over 50% of visibility observations of 5 n mi or more in May to about 35% in June. Gradual improvement occurs in July and August. In the southern third of the Persian Gulf and in the Gulf of Oman, July is the worst month for visibility. Observations taken in the shipping lanes of the Gulf of Oman indicate that visibilities of less than 5 n mi occur 10% to 15% of the time in July, but drop to less than 10% in August.

Coles (1938) found that over land areas surrounding the Persian Gulf the times of start of dust storms are largely influenced by diurnal changes of wind speed. During the "Summer Shamal" wind speeds are generally light at night and free from convectional eddies due to the strong low-level inversion. As the inversion disappears one to two hours after sunrise, turbulence increases rapidly, and surface winds exceed the critical dust-raising speed of about 16 kt. The winds then slack off again about 1800L with a marked decrease in dust being carried aloft. Forecasters should be aware, however, that layers of dust raised during the day usually form a thin lens under the inversion, and the resulting layer of poor visibility at this level can persist for long periods of time. On the day after a major dust storm, visibility at the surface may still be less than one (1) n mi due to settling of suspended dust.

VISIBILITY FORECAST RULE.

a. If the night sounding (or aircraft reports) indicates 1000-ft winds exceed 30 kt in "Summer Shamal" cases with strong low-level inversions at night, radiational heating will cause surface winds strong enough to raise dust the next day.

Fog. Fog is extremely rare during the summer.

Precipitation. Rainfall is rare during the summer season. Occasionally subtropical cyclones will cause weak thunderstorm activity near the northern shores of the Gulf of Oman.

Oceanographic Features

Temperature. Since the Persian Gulf is very shallow, its thermal characteristics are much like a lake. The surface temperature reaches a winter minimum of about 18°C in the northwest corner. This relatively cold, dense water sinks to form the bottom water of the Gulf which stabilizes at about 20°C during the summer, while the surface temperature increases to a maximum of about 33°C. The characteristics of the water in the Gulf of Oman resemble those in the Arabian Sea except on the narrow shelf near the approaches to the Strait of Hormuz where warm, high-density water flows down the shelf slope, depressing the 20°C isotherm to about 1000 ft. Weak upwelling occurs near Ras Al Hadd.

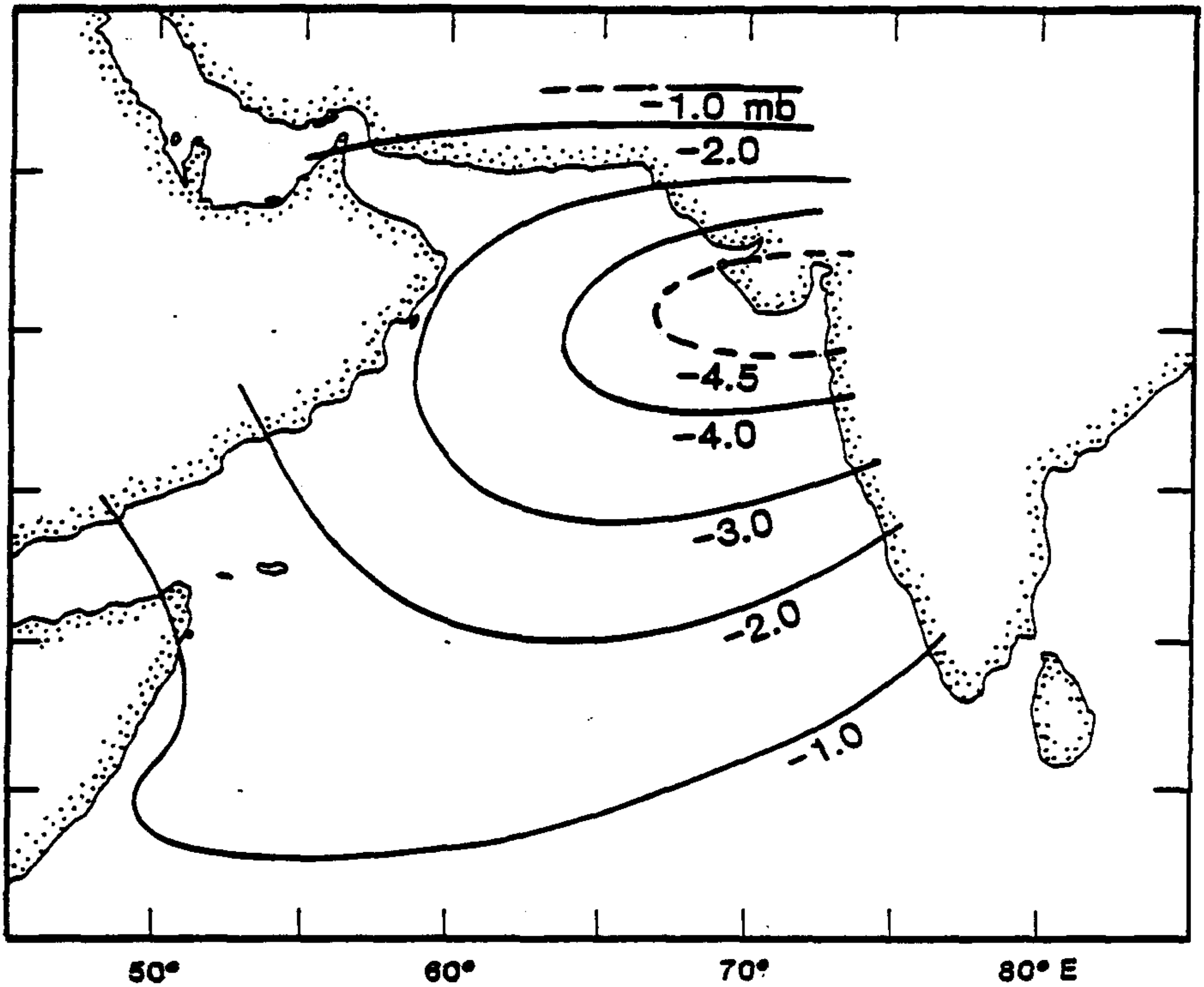
Salinity. Except for the surface layer near the Strait of Hormuz, salinity in the Persian Gulf ranges between 39 o/oo and 40 o/oo. The water which flows back into the Gulf of Oman has a salinity greater than 39 o/oo. Most of the water in the Gulf of Oman is more saline than that found in the Arabian Sea. For example, at about 600 ft, salinities are about 36.5 o/oo versus about 35.3 o/oo at 10°N.

3.3.4 Indian Peninsula

The Southwest Monsoon winds first influence Indian weather during the last week of May or the first week of June. The first effects are often a period of intense convective activity usually associated with an "Onset Vortex". The average date of the onset of the rainy season varies from about May 29 in the south to about June 12 at Bombay. Monthly mean maximum rainfall occurs in June along the southern Indian coast (south of 12°N) but in July farther north. The intensity of the monsoon winds and rain eases in August and decreases sharply in September. Easterly winds accompanied by strong convective activity often signal the end of the Southwest Monsoon near the end of September. A secondary maximum in rainfall occurs in the area south of 10°N in late September and October as the Near Equatorial Trough is re-established.

Monsoon Intensity. The total pressure gradient from south to north in the Arabian Sea is relatively constant from day to day during the summer season. The distribution of this gradient varies significantly, however. Figure 3-12 shows mean pressure differences between "strong" and "weak" monsoon cases. The "anomaly" centered over the Gulf of Canbay causes a weakening of the gradient toward the north and a strengthening of the gradient toward the south. Figure 3-13 depicts typical pressure distributions.

"Strong" Monsoon Patterns (see Figure 3-6). Strong monsoons are characterized by generally weaker winds over the extreme northern Indian Coast and stronger winds along the central Indian Coast. In some cases, a cyclonic eddy exists near the Kathiawar Peninsula causing the southwesterly winds along the coast of Pakistan to veer to the northwest and weaken. Low-tropospheric

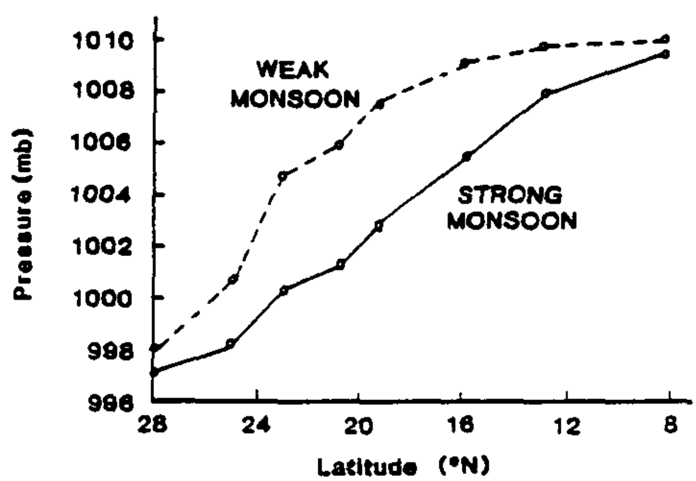


(above)

Figure 3-12. Isopleths of mean pressure differences (mb) between strong and weak Arabian Sea monsoon flow (adapted from Ramamurthy, 1972).

(right)

Figure 3-13. Mean pressure distribution during periods of strong and weak Arabian Sea monsoon flow (adapted from Ramamurthy, 1972).



convergence and associated high-level divergence cause extensive heavy precipitation off the Indian Coast. Orographic effects intensify the precipitation inland. Strong westerly winds occur throughout the lower troposphere between 10°N and 15°N with the maximum near 3,500 ft. Multi-level cloudiness extends 500 to 700 n mi westward from the Indian Coast, and cirrus blow-off often covers most of the Arabian Sea.

"Weak" Monsoon Patterns (see Figure 3-8). "Weak" monsoon conditions do not necessarily indicate universally weaker winds. In fact, the pressure distribution which leads to the "weak" case results in stronger winds along the extreme northern Indian and Arabian Coasts. The wind maximum usually found between 10°N and 15°N from 55°E to 60°E is weaker, however, and its extension toward the central Indian Coast disappears and is replaced by a local minimum near Mangalore. This flow pattern tends to suppress vertical motion and convective activity. Terrain induced cloudiness occurs, but coastal areas may be relatively clear and rainfall is more scattered.

INDIAN COASTAL FORECAST RULES/AIDS.

a. When a Mid-Tropospheric Cyclone occurs over the northern Indian Coast, the most severe weather and greatest vertical cloud development occurs in the southwest quadrant.

b. Westerlies along the Indian Coast south of the Gulf of Canbay extend to a higher altitude (above 500 mb) during strong monsoon cases.

c. Overcast conditions extend 500 to 700 n mi westward from the Indian Coast during strong monsoons.

d. Periods of strong convective activity often mark the beginning and the end of the Southwest Monsoon near the Indian coast.

e. Diurnal effects are minimal during the Southwest Monsoon along the Indian Coast.

f. Wind speeds are lower over the Indian Coast than they are farther to seaward.

g. Thunderstorms are much less frequent during the strongest period (July and August) of the Southwest Monsoon than they are near the beginning and end (June and September).

h. An "Onset Vortex" (see Section 3.2.3) frequently forms near the southern Indian Coast and moves northward just prior to the first "strong" monsoon of the season.

i. Weakening of the upper-level subtropical ridge indicates that a monsoon "break" is likely.

3.3.5 Atlantic Approaches to Arabian Sea

Cloud and Wind Patterns

South of 25°S, conditions similar to those in the North Atlantic in the winter can be expected in both the Atlantic and Indian Oceans. On the Indian Ocean side of Africa, cold surges penetrate northward to at least 15°S, often causing a funneling effect in the Mozambique Channel. Figure 3-14 illustrates an example of a cold front accelerating through the passage. These cold surges strengthen the Southeast Trades, which in turn intensify the Somali Jet and the Arabian Sea Southwest Monsoon. Wind directions tend to parallel the African Coast north of 15°S with an onshore component south of the Equator.

Agulhas Current/Wave Patterns

The Agulhas Current flows in a southwesterly direction parallel to the southeast coast of Africa (see Figure 3-15). It is quite strong (maximum greater than 4 kt) and very narrow (within 100 n mi of the shoreline). The axis of maximum current speed tends to coincide with the 100 fathom depth contour and therefore parallels the edge of the continental shelf. The area shown in Figure 3-15 has been the scene of several supertanker casualties due to current/wave interaction phenomena.

The significance of the Agulhas Current stems from its effect upon ocean wave characteristics. Figure 3-16 shows an idealized wave profile and the profiles resulting from the effects of following and opposing currents on the idealized wave. Two effects are important: changes in wave height and changes in steepness. Significant increases occur in both when the current direction opposes the wave direction. Table 3-1 gives examples of what happens to wave height and length when currents and deep water waves are in opposition.

Southerly waves/swell are common in this area, particularly during the southern hemisphere winter. They tend to approach a "fully developed" state for a given wind speed due to unlimited fetch and duration. When these waves oppose the Agulhas Current, their height and steepness increase spectacularly. The effect is much weaker as the wave encounters lower current speeds closer to shore; therefore, the maximum height and steepness due to this interference phenomenon occur near the core of the current. Analysis of many observations indicates that the waves near shore are usually lower (contain less energy) than those occurring in deep water seaward of the Agulhas Current.

AGULHAS CURRENT FORECAST RULES/AIDS.

a. If strong southerly waves/swell are expected, recommend a track as close to shore as safe navigation will permit (particularly if on a southerly track). If this is not feasible, stay well offshore (outside the 100 fathom line).
b. If the predominant wave/swell is from the northeast, the most comfortable track should be found near the 100 fathom line.
c. If expected waves are slight to moderate from any direction, the effect of the Agulhas Current on speed made good is probably the most important factor in the selection of a track.

3.3.6 Pacific Approaches to Arabian Sea

This section treats routes entering the Indian Ocean via the South China Sea (Strait of Malacca), Java Sea or Australian ports. These routes fall within the "monsoon region" as defined by Ramage (1971). Ships sailing from southern Australian ports do not experience true monsoon weather until they approach the Arabian Sea. Cuming (1973) treats the Bay of Bengal in detail.

Cloud and Wind Patterns

During the Southwest Monsoon, sea level pressure decreases continuously from the subtropical high pressure ridge of the Southern Hemisphere to the heat low over southern Asia. This pressure pattern results in a buffer zone straddling

Figure 3-14. DMSP visual image of the southern African Coast. This photo was selected to illustrate the cloud cover to be expected during an "Atlantic Approach" to the Arabian Sea early in the Southwest Monsoon regime. A weakening cold front is moving northward through the Mozambique Channel and across southern Madagasgar. Clouds over the northern part of Madagasgar indicate onshore flow from the Southeast Trades with a clear area to the lee of the island. Low-level cloud lines over the southern African Coast (see Figure 2-1 for definition) indicate that the southerly flow in that area becomes more southwesterly over the horn of Africa. Over Somalia, the low-level cloud lines are partially obscured by higher-level cloud lines which are nearly perpendicular to the low-level wind direction. These transverse cloud lines are often seen when strong vertical wind shear exists. The difference in altitude of the intersecting cloud lines would be obvious in the IR equivalent of this image. Note that the cirrus plumes near the upper border of the image indicate easterly winds at high altitude. The approximate local sun time at the center of this image is 1130 (0836Z).

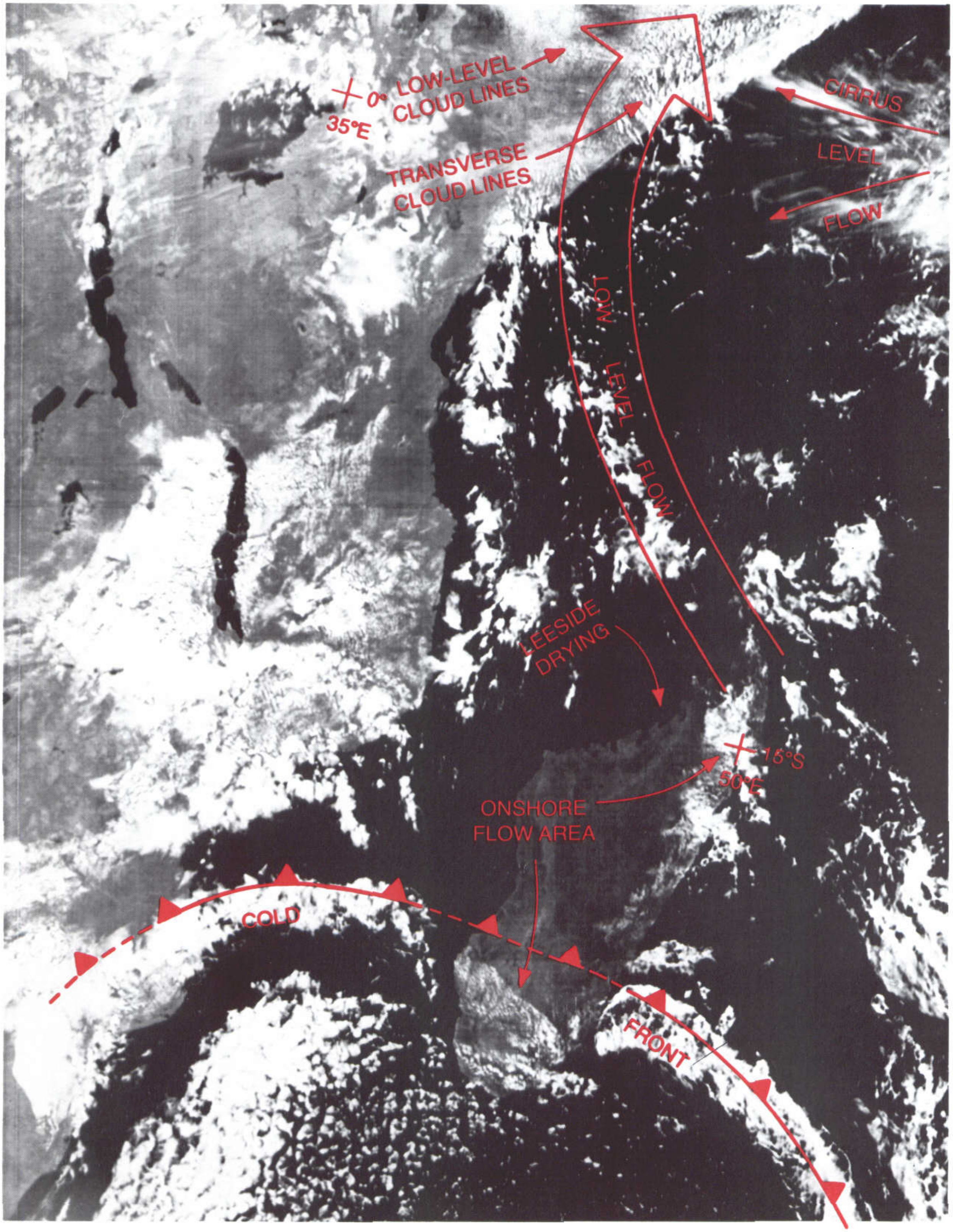


Figure 3-14. DMSP visual image of the southern African Coast and the Atlantic Approaches to the Arabian Sea (June 22, 1979).

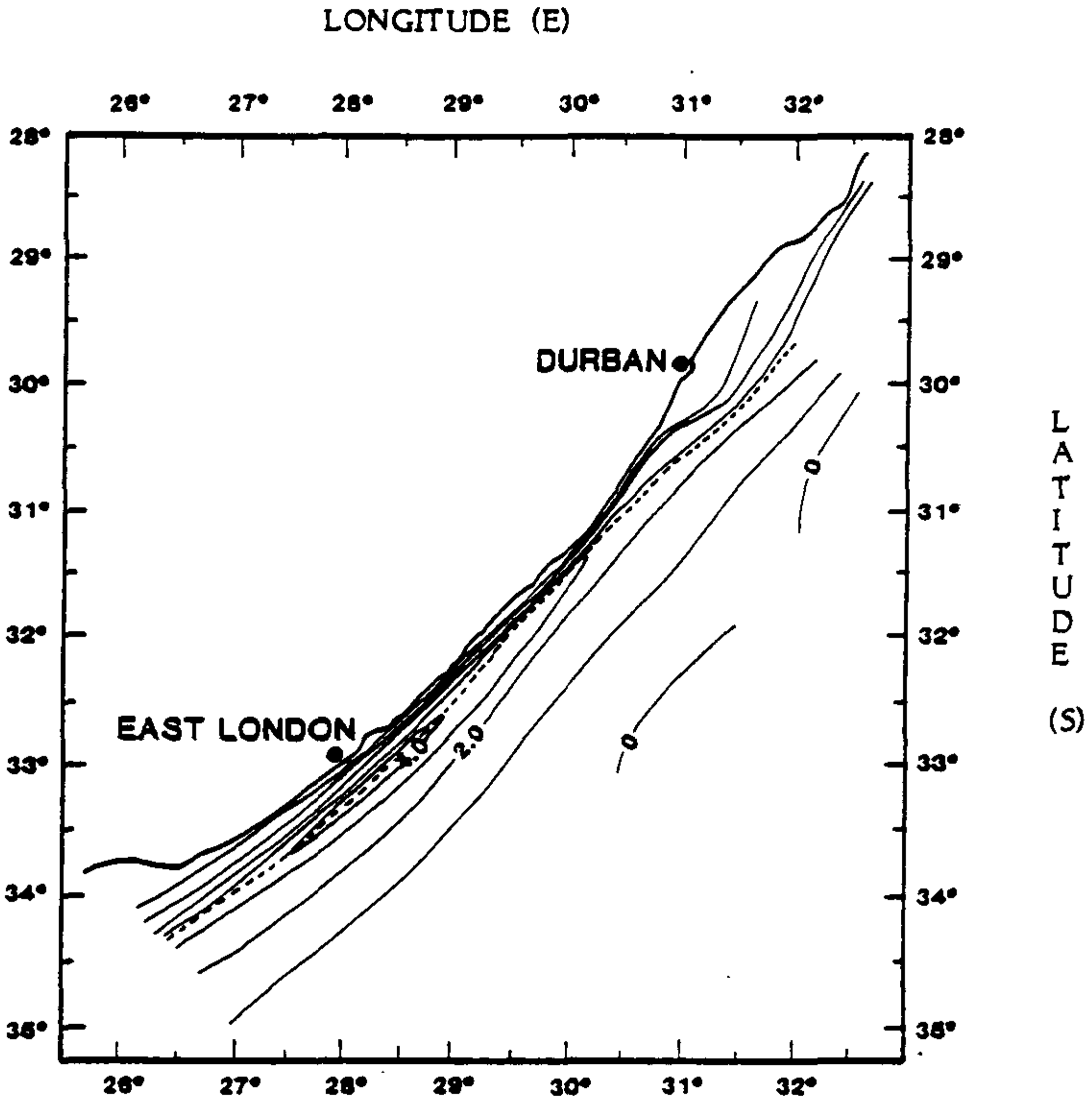


Figure 3-15. Section of southeastern African coast showing Agulhas Current mean speed toward the southwest parallel to the coast. The axis of maximum current speed is shown as a dashed line. The solid lines are current speed in kt (from Schumann and Duncan, 1976).

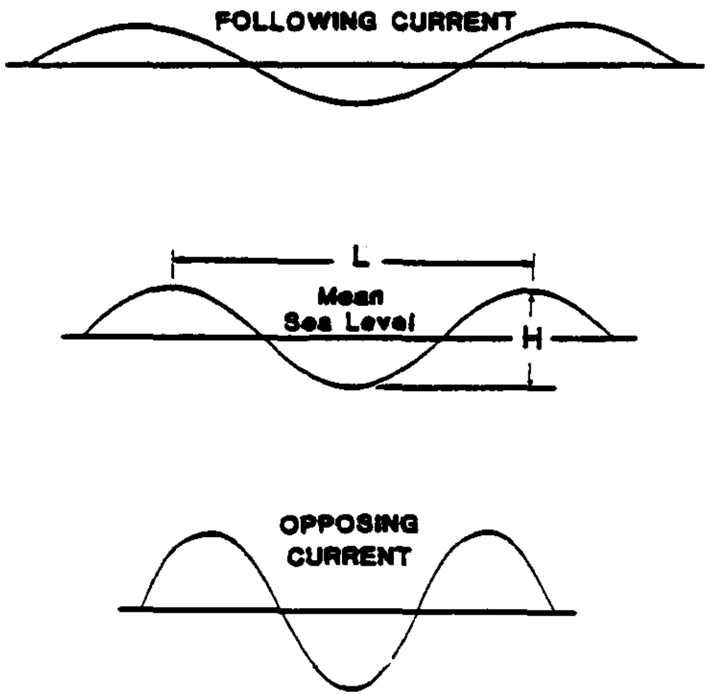


Figure 3-16. An idealized wave profile showing the changes that occur in a following and an opposing current (adapted from Schumann and Duncan, 1976).

Table 3-1. Examples of wave height changes when selected waves with a 10-ft height in deep water meet an opposing current where the current speed is 4 kt.

DEEP WATER WAVE HEIGHT (Ft)	PERIOD (Sec)	DEEP WATER WAVE LENGTH (Ft)	INTERFERENCE WAVE HEIGHT (Ft)	INTERFERENCE WAVE LENGTH (Ft)
10	13	865	13	735
10	10	512	14	384
10	8	328	16	197

the Equator between the Southeast Tradewinds and the Southwest Monsoon. This area is generally characterized by light to moderate southerly winds and scattered to broken cumulus clouds. Scattered light to moderate showers can be expected, particularly near the Equator. Ships on routes from Australia cross the main Southeast Tradewind band ($10^{\circ}S$ - $20^{\circ}S$) where winds to 25 kt can be expected. Ships using the Java Sea route are likely to experience considerable thunderstorm activity, particularly near Selat Sunda. The most direct route through the Strait of Malacca is characterized by broken cumulus, showers and only occasional thunderstorms. Winds and seas on this route may present a problem, particularly on westerly headings. Southwest winds of 10 to 20 kt are most common, but they frequently exceed 20 kt and occasionally reach gale force. Since most winds are steady, they lead to "fully developed" wave heights.

Tropical Cyclones

Tropical cyclones are rare south of $10^{\circ}N$ in the Indian Ocean during the Southwest Monsoon regime.